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The Static Force Calibration of a Skid Resistance Measuring System

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Federal Highway Administration Policy Statement

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Federal Highway Administration.

Foreword

This report was drafted in May, 1973 to describe calibration tests conducted by the authors on the skid resistance measuring system designated by the FHWA as the Interim Reference System. Since that time, the skid trailer has undergone several modifications, therefore the data reported here may not represent the IRS as it exists today. The equations and techniques, however, still apply to the IRS and similar skid measuring systems, and may be useful to anyone involved in skid resistance measurement programs.

The text has been revised from the 1973 draft.

In view of present accepted practice in this technological area, U.S. customary units of measurement have been used throughout this paper. It should be noted that the U.S.A. is a signatory to the General Conference on Weights and Measures which gave official status to the metric SI system of units in 1960. Readers interested in making use of the coherent system of SI units will find conversion factors in ASTM Standard Metric Practice Guide, ASTM Designation E 380-70 (available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103).

Length	1 in = 0.0254* meter
Area	1 in^2 = 6.4516* x 10^{-4} $meter^2$
Force	1 lbf = 4.448 newton

*Exact values

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THE STATIC FORCE CALIBRATION
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SKID RESISTANCE MEASURING SYSTEM

R. W. Kearns and J. F. Ward

ABSTRACT

A variety of skid resistance measuring systems have been designed to meet the requirements of ASTM Method E 274. When these systems are compared on the same pavement, the measurements often vary widely. This report describes procedures for the calibration and control of one such measuring system, the FHWA Interim Reference System. This system employs a tow vehicle and two-wheeled skid trailer. The procedures are chosen to minimize errors, leading to an increased confidence in the measurement results.

Equations of static equilibrium for the skid trailer are derived and experimentally verified. The motions of the system in response to static force are measured and shown to depend on tow vehicle as well as trailer characteristics. Variables affecting the force calibration are identified. These include hitch height, trailer weight, lateral force on the test tire, center of support of the test tire, temperature of the test tire and force transducer, and inflation pressure.

The use of a force plate as a calibrator is described. It is shown that the calibrator must itself have been calibrated under conditions covering its use with the trailer. Calibration of the force plate under combined vertical and traction force is described.

The procedures are adaptable to other similar skid resistance measuring systems.

Key Words: Accident reduction, skidding; highway safety; measurement, skid resistance; pavement skid resistance; skid resistance measurement; tire-pavement interface forces; wet pavement skid resistance.

1. INTRODUCTION

The improvement of the skid resistance at the tire wet-pavement interface is one of the important means of reducing automotive traffic accidents. Slippery pavements must be identified before the condition can be corrected. One means of identifying slippery pavements is to measure the skid resistance using ASTM Method E 274-70. There are a variety of skid resistance measuring systems whose design is reported to meet the requirements of the method. Unfortunately, the measurements made with these systems lack precision and measurements made by these systems on the same pavement vary widely. The trailer and tow vehicle of the FHWA interim reference system (IRS) are shown in figure 1. The method utilizes a measurement of the horizontal traction force on a locked standard test tire (ASTM E 249-66) as it is dragged over a wetted pavement surface under constant load and at a constant speed while its major plane is parallel to the direction of motion and perpendicular to the pavement. In the system shown, the test tire is mounted on a towed two-wheel trailer. The wetting of the pavement is controlled in amount and distribution with the assistance of a flow channel located ahead of the test tire. The horizontal traction force and the vertical wheel load force are detected by a transducer associated with the test wheel. The wheel transducer signals are conditioned and recorded within the tow vehicle. The tow vehicle contains a supply of water. The system also includes a speed detector and associated calibration equipment.

This report is directed toward one phase of the measurement process -- the static calibration of the wheel transducer when it is mounted on the trailer and a traction force is applied at the tire-pavement interface. The traction force is applied by means of a force plate which establishes a reference plane for the traction force. The traction force is not the only force acting at the tire-pavement interface. The vertical wheel load acts at the tire-pavement interface and an axial force may or may not act there also. While the traction force applied by the force plate is the input to the skid resistance measuring system and the signal from the traction channel of the wheel transducer is the desired output from the system, the design of the trailer and its method of use affect the transfer from input to output.

The three dimensional force acting at the tire force-plate interface varies with the magnitude of the input force, the system design characteristics, and the characteristics of the force plate. The characteristics of the force plate may alter the output signal from the wheel transducer, since the force plate may not accurately simulate the tire-pavement interface forces occurring in highway use. The effect of the input traction force on the displacement of the system is discussed in section 2. The forces and moments applied to the wheel transducer are discussed in section 3. The calibration equipment and the calibration procedures for the force plate itself are discussed in section 4. Errors in the measurement process can occur, but their effect can be minimized as discussed in section 4. The calibration procedures can

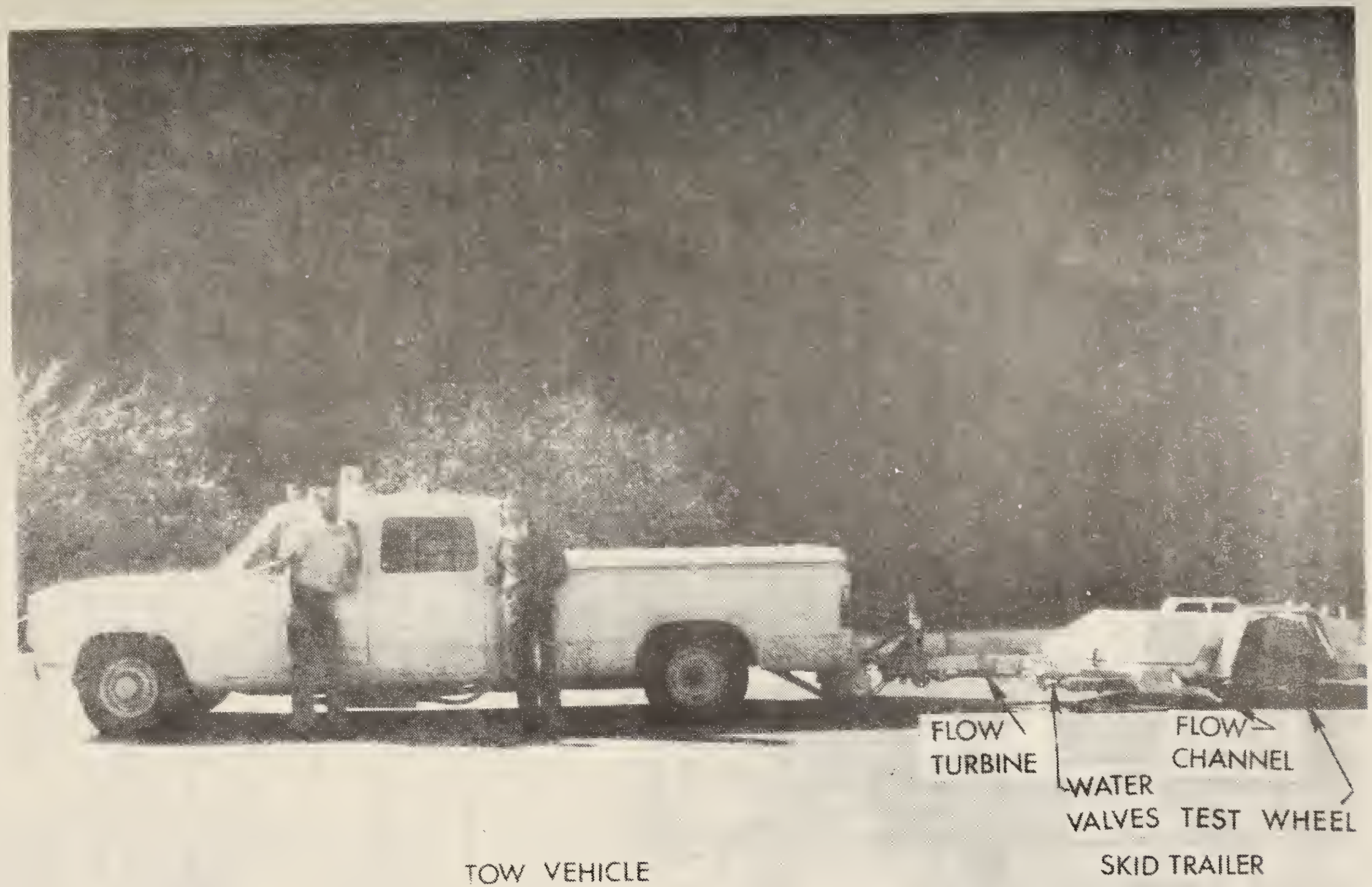

Figure 1. The FHWA interim reference skid measuring system.

affect the results of calibrating the wheel transducer which is discussed in section 4. The calibration is conducted under static conditions, however, the conditions change during operation. The effect of certain changes can be estimated from the discussion in section 5. These changes can be related to changes in skid number which is discussed in section 3.

While the numerical values apply to the FWHA interim reference system (IRS) as of this date, the process and techniques can be repeated on any system to verify the skid measuring system design and analysis with tests and observations. The correlation between theory and measurement will lead to an increased level of confidence in the measurement results and may identify other parameters which should be controlled during calibration and use of the system.

2. CHARACTERISTIC MOTIONS OF THE SYSTEM

The trailer and tow vehicle system can be described by a set of mathematical equations relating the input to the output of the system. A block diagram is a simplified device for the same purpose. The physical elements appearing in block diagrams are described by a term called the "transfer function." An input traction force at the tire-pavement interface is modified by the transfer function of the trailer and tow vehicle to an output from the wheel transducer. From a knowledge of the output from the wheel transducer alone, it is impossible to distinguish between a change in the tire-pavement traction force and a change in the transfer function of the trailer and tow vehicle. The transfer function of the IRS is such that during the static force calibration, the application of the horizontal traction force changes the equilibrium forces of the skid measurement system resulting in translation and rotation of the trailer body, trailer axle, and tow vehicle. A detailed knowledge of these changes is helpful in the design of calibration equipments and test procedures. Application of this knowledge can minimize measurement errors by controlling additional variables of the measurement process and guiding system design improvements. In this section, the applicable force equations and the translations and rotations of the IRS trailer are given. Also, the correlation between theory and measurements is experimentally verified.

2.1. Equations of Static Equilibrium

A free body diagram of the skid trailer is shown in figure 2. The diagram is more general than that required by the ASTM method in that there is provision for a horizontal traction force at both wheels. In the following paragraphs, we develop equations for each of the external forces acting on the trailer as a function of the horizontal traction force, which is the input to the system. In the equations,

x = the horizontal longitudinal axis

y = the vertical axis

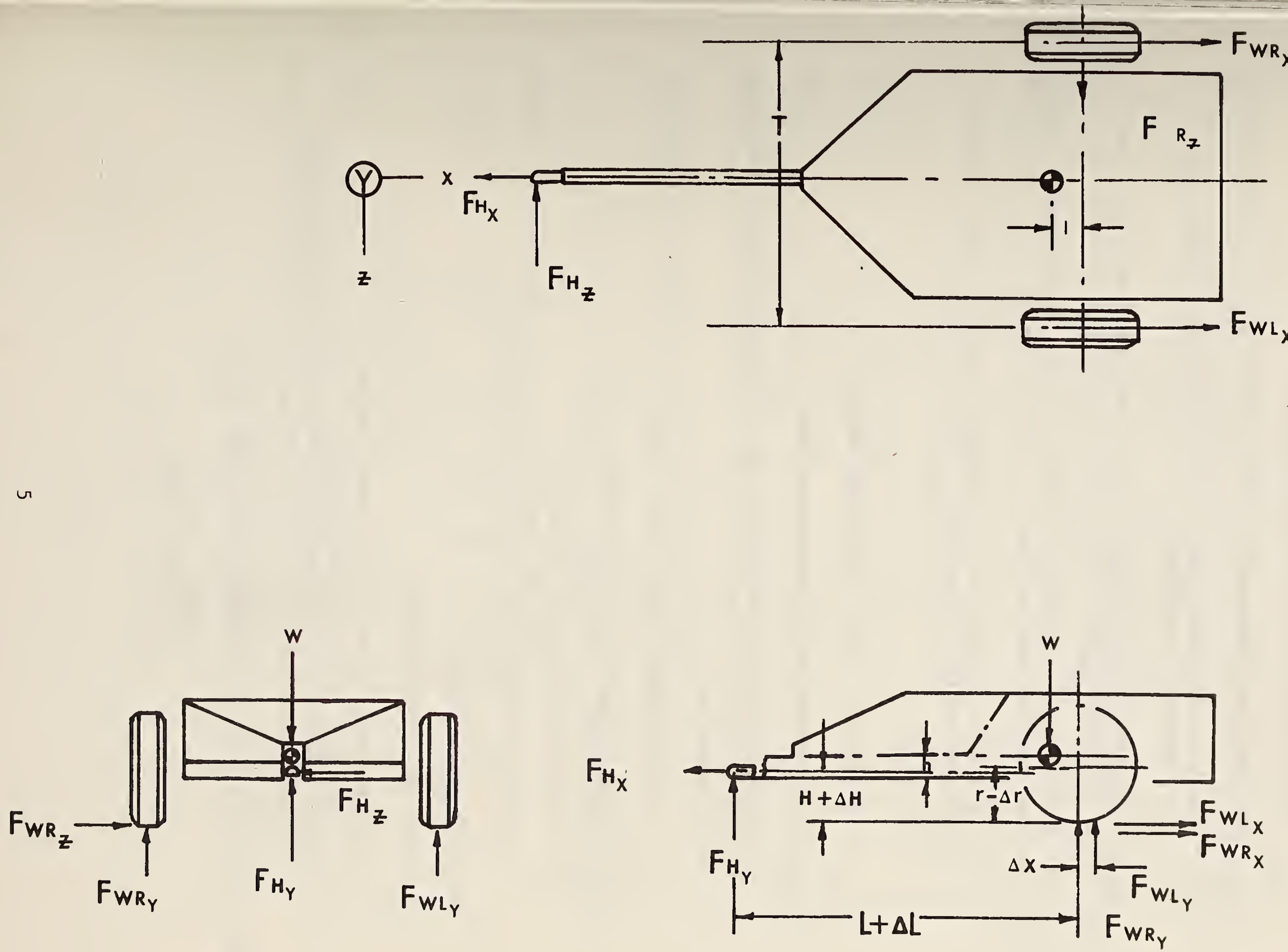

Figure 2. Free body diagram of skid trailer with traction applied.

z = the horizontal (lateral) axis

F_{WL_x} = the traction force on the left wheel

F_{WR_x} = the traction force on the right wheel

F_{WL_y} = the total vertical force on the left wheel acting at the tire-pavement interface

F_{WR_y} = the total vertical force on the right wheel acting at the tire-pavement interface

ΔX = the effective longitudinal position of F_{WL_x} with respect to the wheel vertical center line

r = the distance between the tire-pavement interface and the wheel horizontal center line when $F_{WL_x} = 0$

Δr = the change in r

F_{WR_z} = the lateral force on the right wheel

F_{WL_z} = the lateral force on the left wheel

L = the length from the center line of the trailer wheel to the hitch

ΔL = the change in L

F_{H_x} = the longitudinal force on the hitch

F_{H_y} = the vertical force on the hitch

F_{H_z} = the lateral force on the hitch

H = the height from a level pavement to the hitch

ΔH = the change in H

W = the total trailer weight

T = trailer wheel track width, center-to-center

ℓ = the location of the center-of-gravity along the longitudinal center line with respect to the trailer axle.

When a traction test is performed on the left wheel,

$$F_{WL_x} > F_{WR_x}$$

and since an air-bearing force plate is used

$$F_{WL_z} = 0.$$

Referring to the trailer top view and summing moments about the hitch,

$$F_{WL_x}\left(\frac{T}{2}\right) = F_{WR_x}\left(\frac{T}{2}\right) + F_{WR_z} L \ ,$$

or

$$\left(F_{WL_x} - F_{WR_x}\right)\frac{T}{2L} = F_{WR_z} \ . \qquad (1)$$

Refering to the trailer end view and summing moments about the hitch again,

$$F_{WR_z} H + F_{WL_y}\left(\frac{T}{2}\right) = F_{WR_y}\left(\frac{T}{2}\right)$$

or

$$F_{WR_z}\frac{2H}{T} + F_{WL_y} = F_{WR_y} \ . \qquad (2)$$

Referring to the trailer side view and summing moments about the hitch,

$$W(L-\ell) = (F_{WR_y} + F_{WL_y}) L + (F_{WR_x} + F_{WL_x}) H. \quad (3)$$

Substituting equation 2 into equation 3, we obtain

$$W(L-\ell) = 2\left[F_{WR_z}\frac{H}{T} + F_{WL_y}\right] L + (F_{WR_x} + F_{WL_x}) H \ . \quad (4)$$

Substituting equation 1 into equation 4, we obtain

$$W(L-\ell) = 2\left[(F_{WL_x} - F_{WR_x})\frac{T}{2L}\ \frac{H}{T} + F_{WL_y}\right] L + (F_{WR_x} + F_{WL_x}) H$$

$$= 2\,(F_{WL_x} H + F_{WL_y} L). \qquad (5)$$

When $F_{WL_x} = 0$, $F_{WL_y} = F_{WL_{yo}}$. Substituting this into equation 5, and re-arranging we obtain

$$F_{WL_{yo}} = W\frac{(L-\ell)}{2L} \ ,$$

or

$$\ell = L\left(1 - 2\frac{F_{WL_{yo}}}{W}\right). \qquad (6)$$

Substituting equation 6 into equation 5, we obtain

$$WL - W\left[L\left(1 - 2\frac{F_{WL_{yo}}}{W}\right)\right] = 2(F_{WL_x} H + F_{WL_y} L),$$

or

$$F_{WL_y} = F_{WL_{yo}} - F_{WL_x}\left(\frac{H}{L}\right) . \qquad (7)$$

Equation 7 indicates that the vertical force on the test wheel decreases as the horizontal traction force on the test wheel increases. This result is used later in developing the force plate calibration procedures.

The skid resistance of the paved surface is reported as skid number, SN, which is defined under the conditions of E 274 by the equation

$$SN = \frac{F_{WL_x}(100)}{F_{WL_y}} = \frac{F_{WL_x}(100)}{F_{WL_{yo}} - F_{WL_x}\left(\frac{H}{L}\right)} \qquad (8)$$

in which

F_{WL_x} = the force required to slide the locked test tire at a stated speed while encountering a controlled water layer, and

F_{WL_y} = the effective wheel load.

The reduction of vertical load on the free wheel is obtained by substituting equation 1 into equation 2, giving

$$(F_{WL_x} - F_{WR_x})\frac{T}{2L}\left(\frac{2H}{T}\right) + F_{WL_y} = F_{WR_y} . \qquad (9)$$

Substituting equation 7 into equation 9, we obtain

$$(F_{WL_x} - F_{WR_x})\frac{H}{L} + F_{WL_{yo}} - F_{WL_x}\left(\frac{H}{L}\right) = F_{WR_y}$$

or

$$F_{WL_{yo}} - F_{WR_x}\left(\frac{H}{L}\right) = F_{WR_y} .$$

But for a symmetrical weight distribution

$$F_{WL_{yo}} = F_{WR_{yo}} ,$$

therefore,

$$F_{WR_y} = F_{WR_{yo}} - F_{WR_x} \left(\frac{H}{L}\right) , \tag{10}$$

or the vertical force on the free wheel behaves as the vertical force on the test wheel. However, as the free wheel has no traction force occurring, the vertical force on the free wheel does not change from the "at rest" value.

To obtain the variation of the load on the hitch as a function of traction we refer to the trailer side view again and use the sum of the forces in the vertical direction to get

$$F_{H_y} + F_{WL_y} + F_{WR_y} = W ,$$

or

$$F_{H_y} = W - F_{WL_y} - F_{WR_y} \tag{11}$$

Substituting equations 10 and 7 into equation 11, we obtain

$$F_{H_y} = W - F_{WL_{yo}} + F_{WL_x} \frac{H}{L} - F_{WR_{yo}} + F_{WR_y} \frac{H}{L}$$

$$= W - F_{WL_{yo}} - F_{WR_{yo}} + (F_{WL_x} + F_{WR_x}) \frac{H}{L} .$$

But,

$$W - F_{WL_{yo}} - F_{WR_{yo}} = F_{H_{yo}} .$$

Therefore,

$$F_{H_y} = F_{H_{yo}} + 2 (F_{WL_x} + F_{WR_x}) \frac{H}{L} . \tag{12}$$

Equation 12 indicates that the hitch force increases by the amount the vertical forces on the wheels decrease. When there is no traction on the free wheel, the hitch force increases by the amount the vertical force on the test wheel decreases.

An expression for the lateral force on the test wheel is not developed here. During a wheel load transducer calibration using an air-bearing force plate, the lateral force on the test wheel is zero. Should the force plate resist a lateral force developed at the test wheel the total lateral force as given by equation 1 is shared between both trailer wheels.

A summary of the static equilibrium force equations of the skid trailer is given in table 1.

Table 1. Summary of static equilibrium forces (with $F_{WR_x} = 0$)

Force	Equation	
Lateral force on the free tire	$F_{WR_z} = F_{WL_x} \left(\frac{T}{2L}\right)$	(1)
Vertical force on the test tire	$F_{WL_y} = F_{WL_{yo}} - F_{WL_x} \left(\frac{H}{L}\right)$	(7)
Skid number	$SN = \dfrac{F_{WL_x}(100)}{F_{WL_{yo}} - F_{WL_x}\left(\frac{H}{L}\right)}$	(8)
Vertical force on the free tire	$F_{WR_y} = F_{WR_{yo}}$	(10)
Vertical force on the hitch	$F_{H_y} = F_{H_{yo}} + \Delta F_{WL_y}$	(13)
Lateral force on the hitch	$F_{H_z} = F_{WR_z} = F_{WL_x} \left(\frac{T}{2L}\right)$	
Longitudinal force on the hitch	$F_{H_x} = - F_{WL_x}$	

2.2. Traction Induced Motions

The changes in the equilibrium forces with the application of the horizontal traction force, as previously described, result in translations and rotations of the trailer and tow vehicle. Since the wheel transducer is mounted on the axle, which in turn is coupled to the trailer body through the suspension system, the movement of the trailer changes the output from the wheel transducer. In this section, the translations and rotations accompanying the application of a static horizontal traction force will be identified and quantified. It will also be shown that a given skid trailer will have a different static (and hence dynamic) behavior when the tow vehicle and/or the tires of either vehicle are changed since the tow vehicle characteristics and the tire characteristics of both the tow vehicle and trailer influence the translations and rotations of the trailer body.

From equation 1 it can be seen that as the force plate traction is increased, lateral force is generated at the free-wheel tire-pavement interface. For equilibrium, an opposing lateral force is developed at the hitch point. The lateral force at the hitch acts through the trailer body which transfers the force to the trailer axle through the suspension system springs and the sway bar. (The suspension system details for the trailer are shown in figure 3.) Thus there is a displacement of the trailer body with respect to the axle. The hitch force appears at the axle and places the free tire in shear with the lateral force at the tire-pavement interface. The shearing of the tire results in a vertical displacement of the axle with respect to the pavement as can be seen from figure 4. Displacements are measured at the points numbered in figure 5.

The lateral displacement of the axle with respect to the pavement due to changes in horizontal traction force are given in figure 6. The displacement of the trailer body with respect to the pavement due to changes in traction force is given in figure 7. At 800 pounds of traction force the axle moves laterally, in the opposite direction to the lateral tire-interface force, 0.37 inches, and the body moves 0.57 inches.

The shearing of the free tire is accompanied by a decrease in the free wheel radius as shown in figure 8. At 800 pounds of traction, the axle moves downward 0.05 inches. The tire on the free wheel of the FHWA interim reference system was an ASTM E 249-66 standard test tire.

The horizontal force developed at the hitch is resisted by the tow vehicle. In a similar manner to that already described, the tow vehicle suspension and tow vehicle tires are subjected to the same shear force. The variation in displacement of the hitch and axle of the tow vehicle with variation in traction force are given in figures 9 and 10 respectively. The hitch is displaced 0.25 inches and the axle displaced 0.12 inches toward the test side when the traction force is 800 pounds.

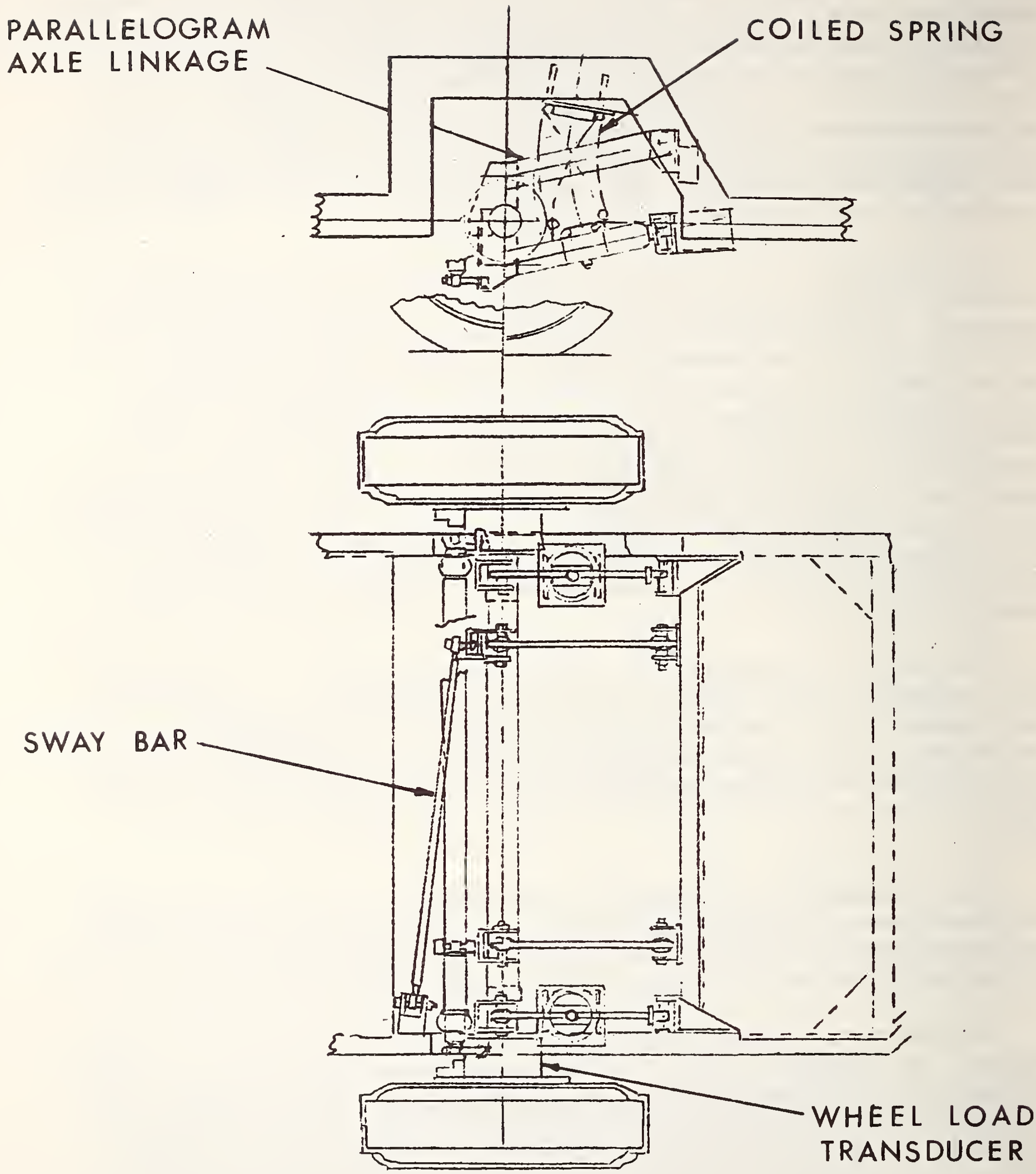

Figure 3. Suspension details.

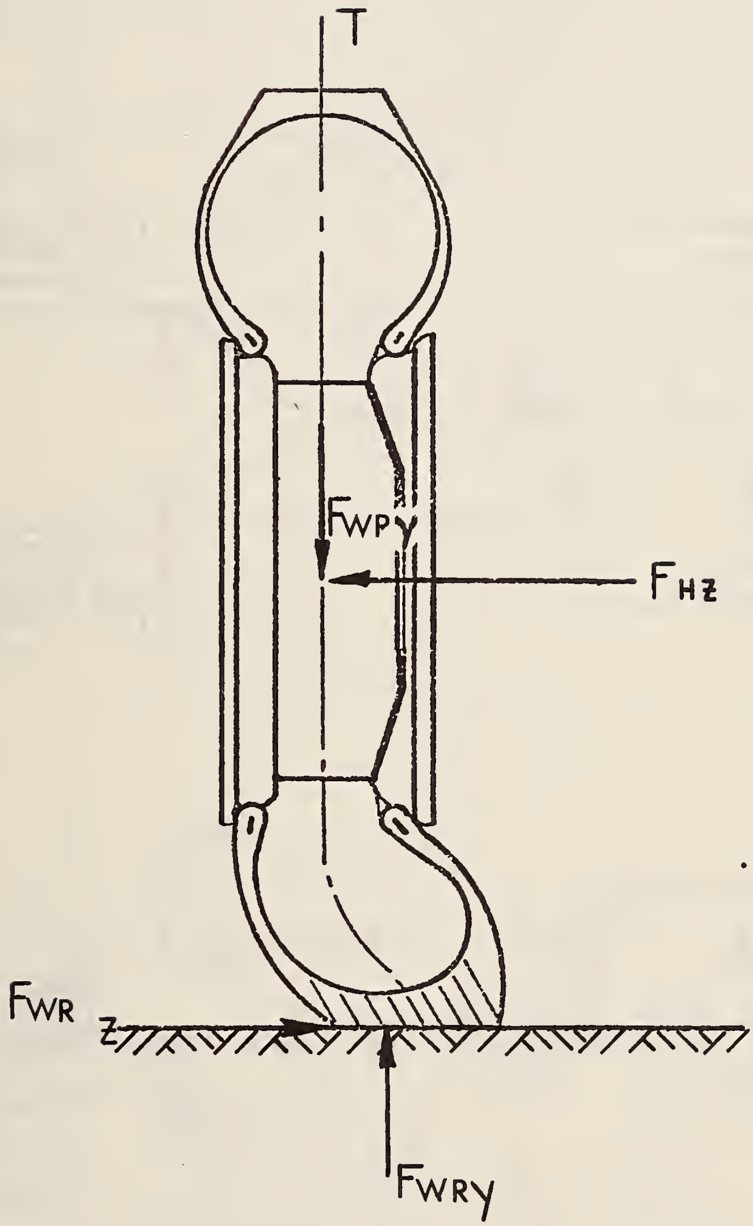

Figure 4. Shearing of the free tire (front view).

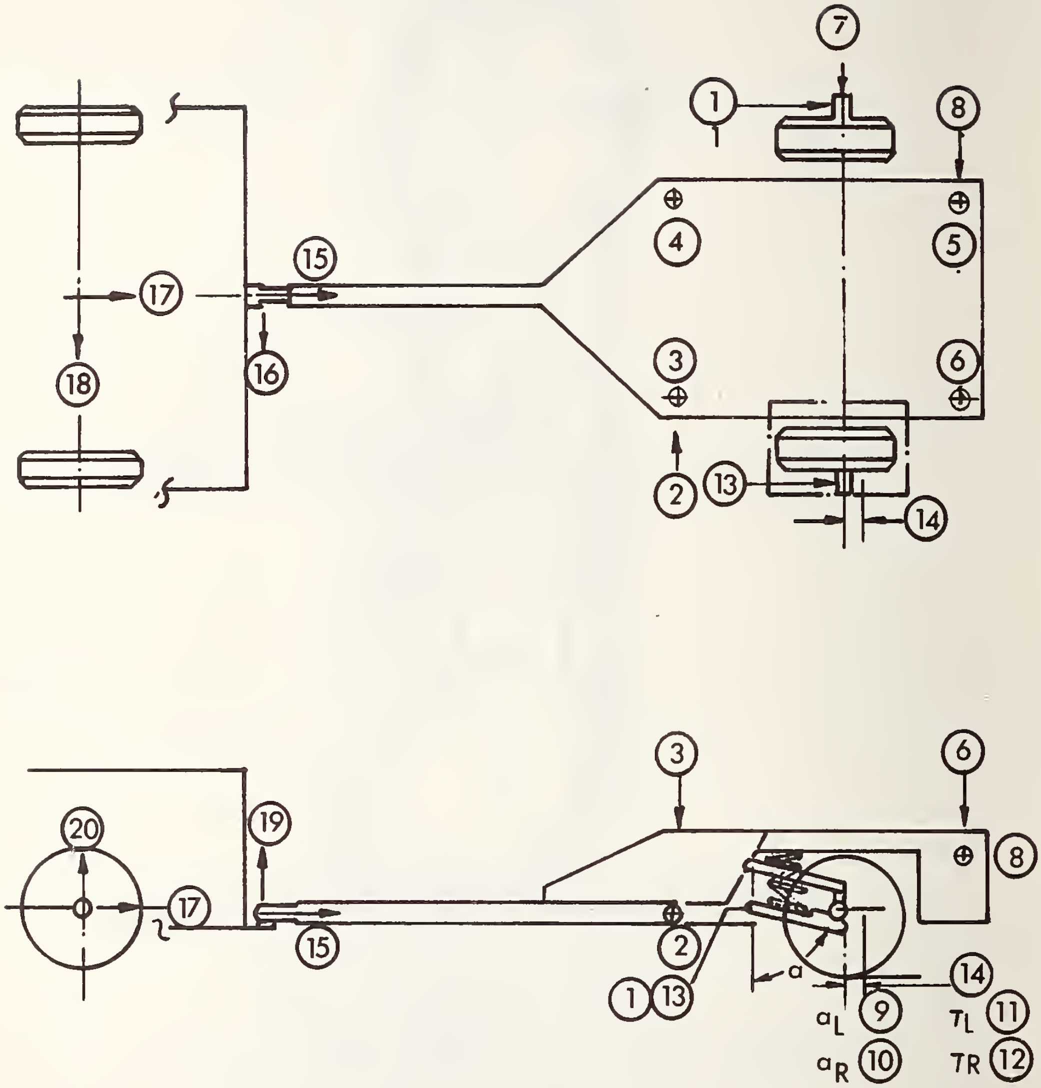

Figure 5. Trailer displacement measurement locations.

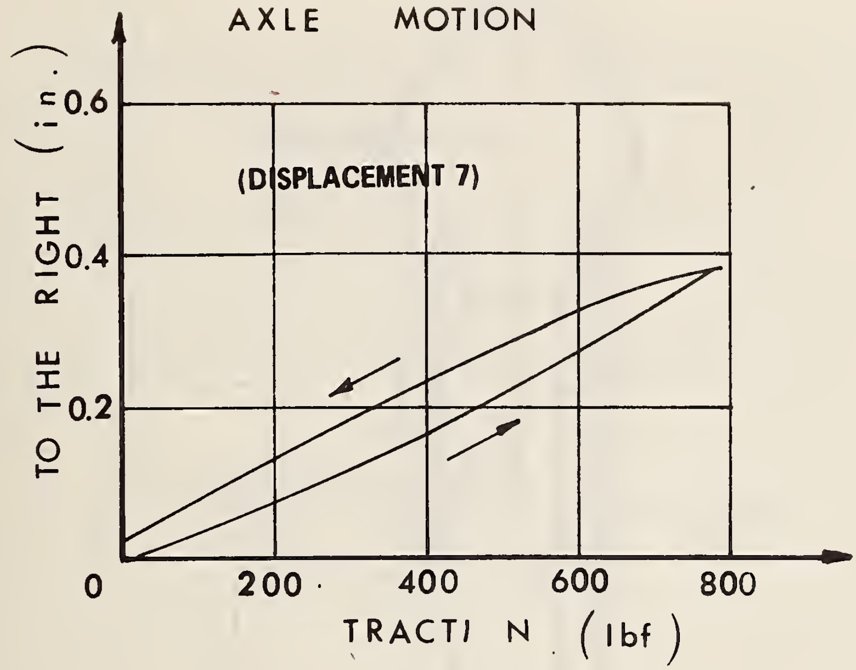

Figure 6. Lateral displacement of the axle.

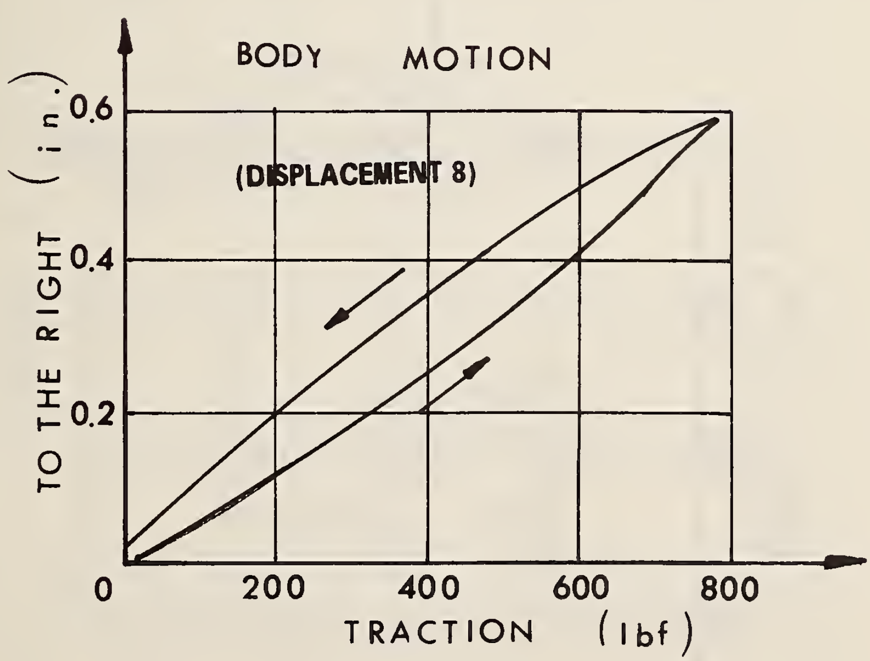

Figure 7. Displacement of the trailer body at location 8.

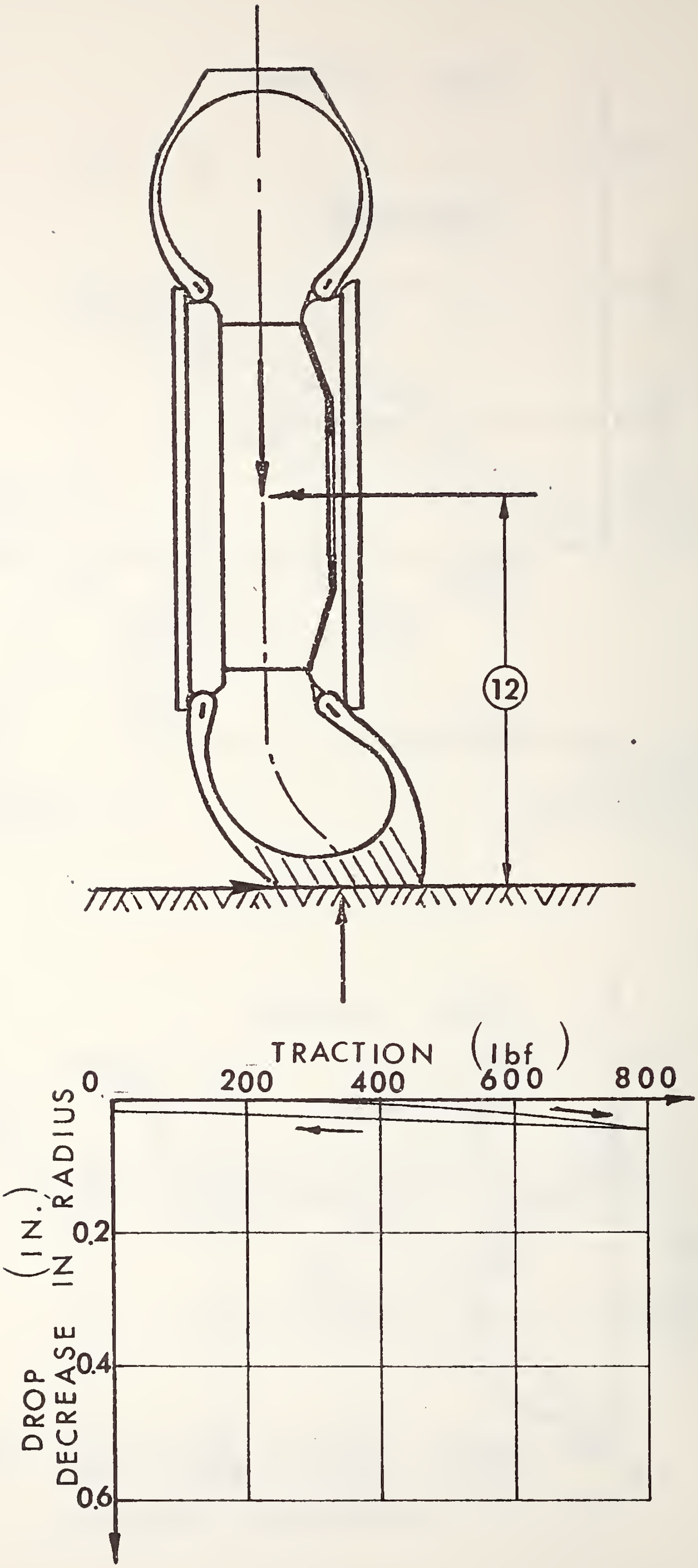

Figure 8. Shearing of the free tire and decrease in radius.

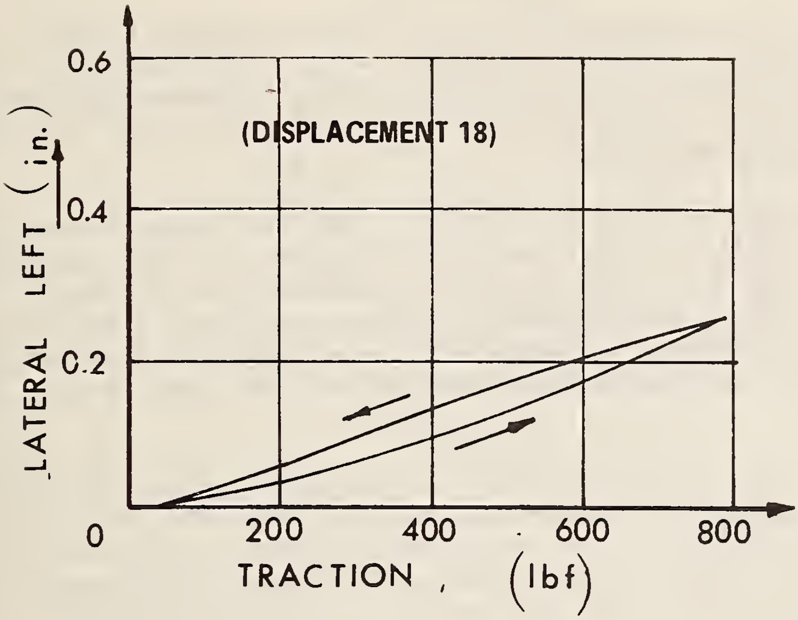

Figure 9. Lateral displacement of the hitch.

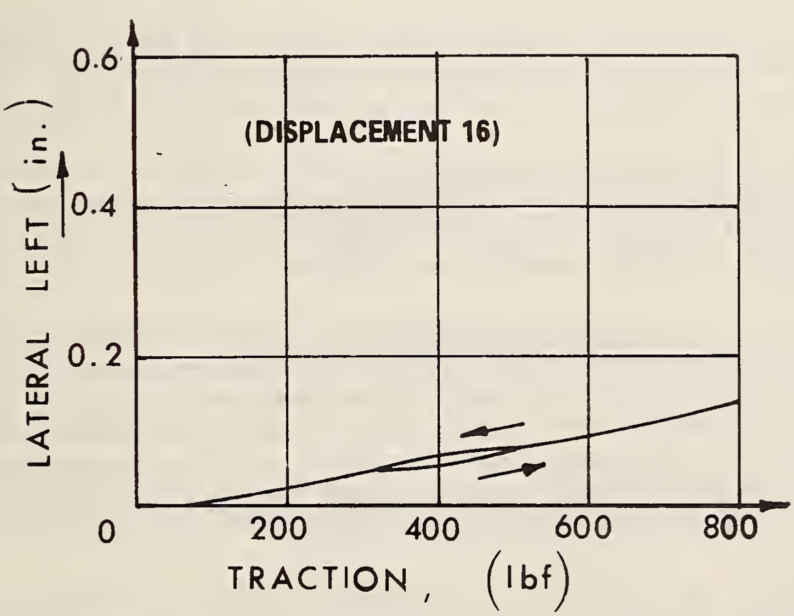

Figure 10. Lateral displacement of the tow vehicle axle.

The test wheel radius changes too, but it increases since the vertical load on the test tire decreases as traction increases. (See eq. 7.) The increase in test tire radius with increase in traction is shown in figure 11. At 800 pounds of traction force, the test wheel radius increases 0.05 inches.

During a force plate test the hub of the free wheel moves forward very slightly as the traction force is increased. At 800 pounds of traction force the free wheel hub moves forward 0.020 inches. This displacement is given in figure 12. However, during a force place test the test wheel hub moves rearward 0.70 inches when the traction force is 800 pounds. The rearward displacement of the test wheel hub is given in figure 13.

During a force plate test, the trailer body rotates in roll, pitch, and yaw. The displacement measurements associated with roll and pitch are made at locations 3, 4, 5, and 6 and are shown in figure 14. Location 6 is lower than location 5 and location 3 is lower than location 4 by approximately 1.1 inches when the traction force is 800 pounds. This 1.1 inch displacement is in roll attitude. Location 3 is lower than location 6 and location 4 is lower than location 5 by 0.15 inches when the traction force is 800 pounds. This 0.15 inch displacement is in pitch attitude. Yaw attitude changes are related to rotation about an instant center and will be discussed later. A displacement of location 2 is related to yaw and is given versus traction force in figure 15.

The complete displacement of the hitch is given in figure 16 while the complete displacement of the tow vehicle rear axle is given in figure 17.

The rotation of the left parallelogram suspension arms is given in figure 18 while the rotation of the right is given in figure 19. The rotation is plotted as a deviation from the orientation with $F_{WL_x} = 0$.

The rearward displacement of the force plate with respect to the axle is given in figure 20 while the vertical force sustained by the test wheel is given in figure 21. No slipping of the force plate with respect to the tire or of the brakes was observed.

Experiments were conducted and measurements made to confirm the changes in force stated by the equations. Also, the variation in internal forces was calculated to confirm the observed change in length of the suspension springs. The correlation of theory and measurement enhances the degree of confidence one can place in the output measurements. After the system is modified and ready for use, additional detailed work will be appropriate in this section.*

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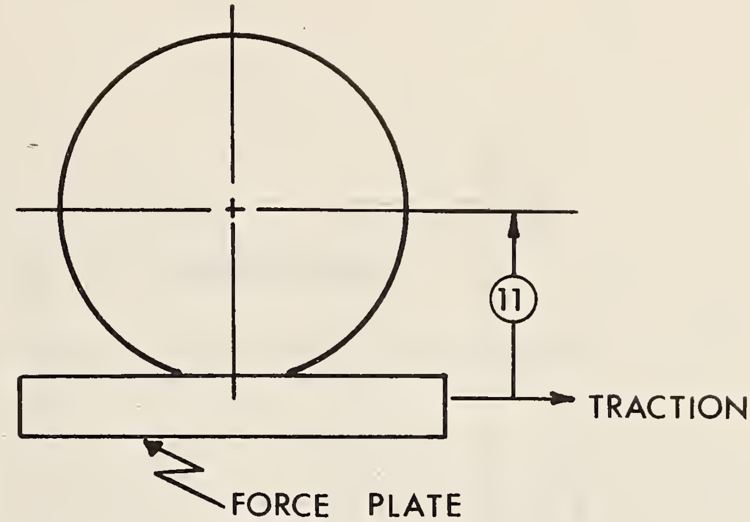
*Since this material was written, the suspension has been modified such that the parallelogram trailing arms are horizontal when the trailer is at rest. With this arrangement, arm rotation and trailer body roll due to traction have been substantially eliminated.



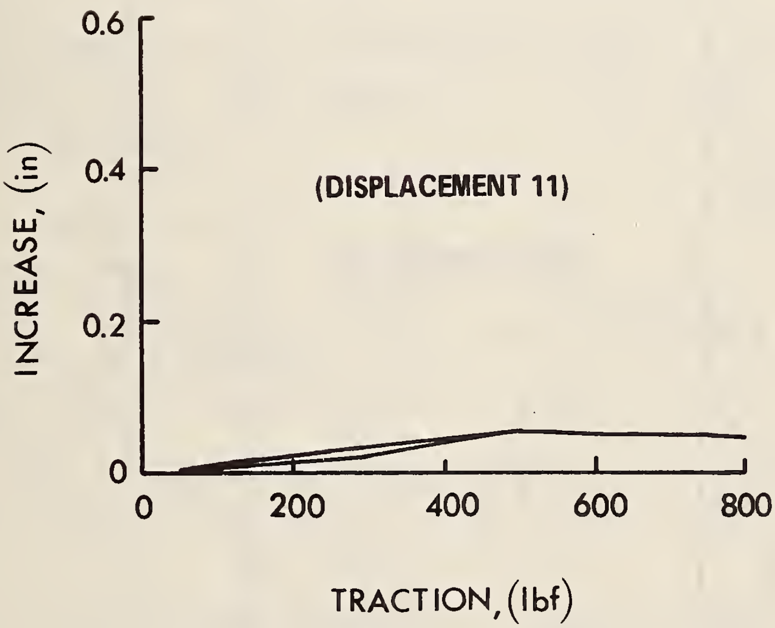


Figure 11. Increase in test wheel radius.

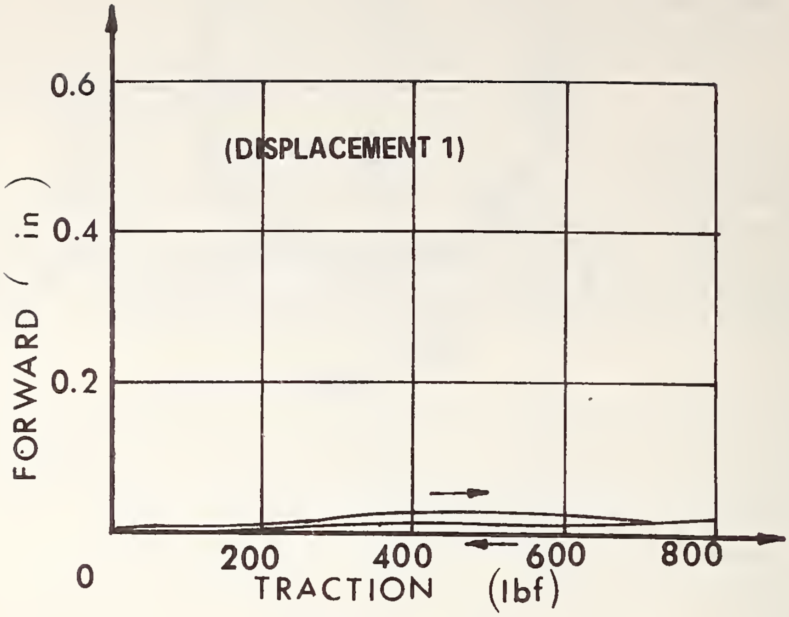


Figure 12. Forward displacement of the free wheel hub.

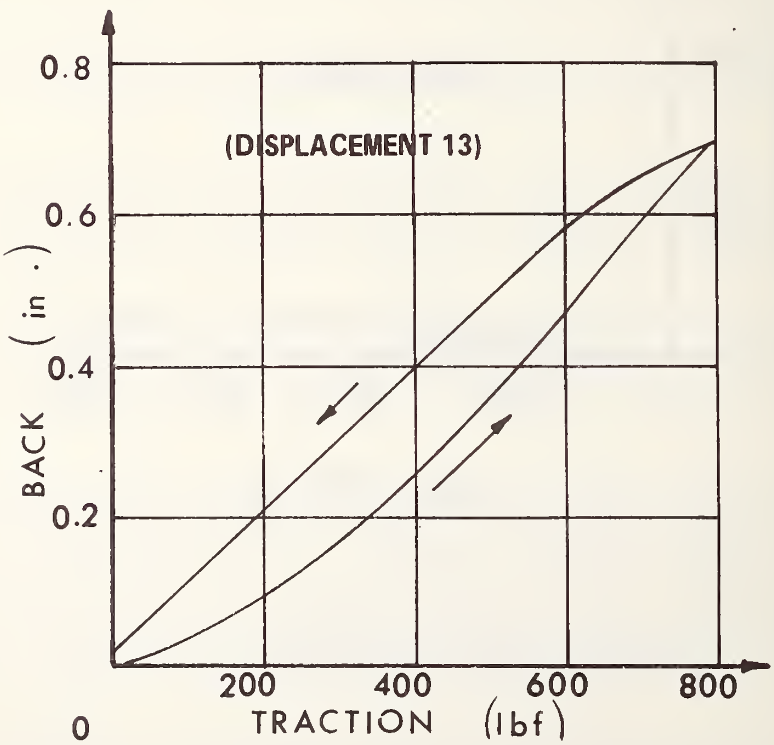


Figure 13. Rearward displacement of the test wheel hub.

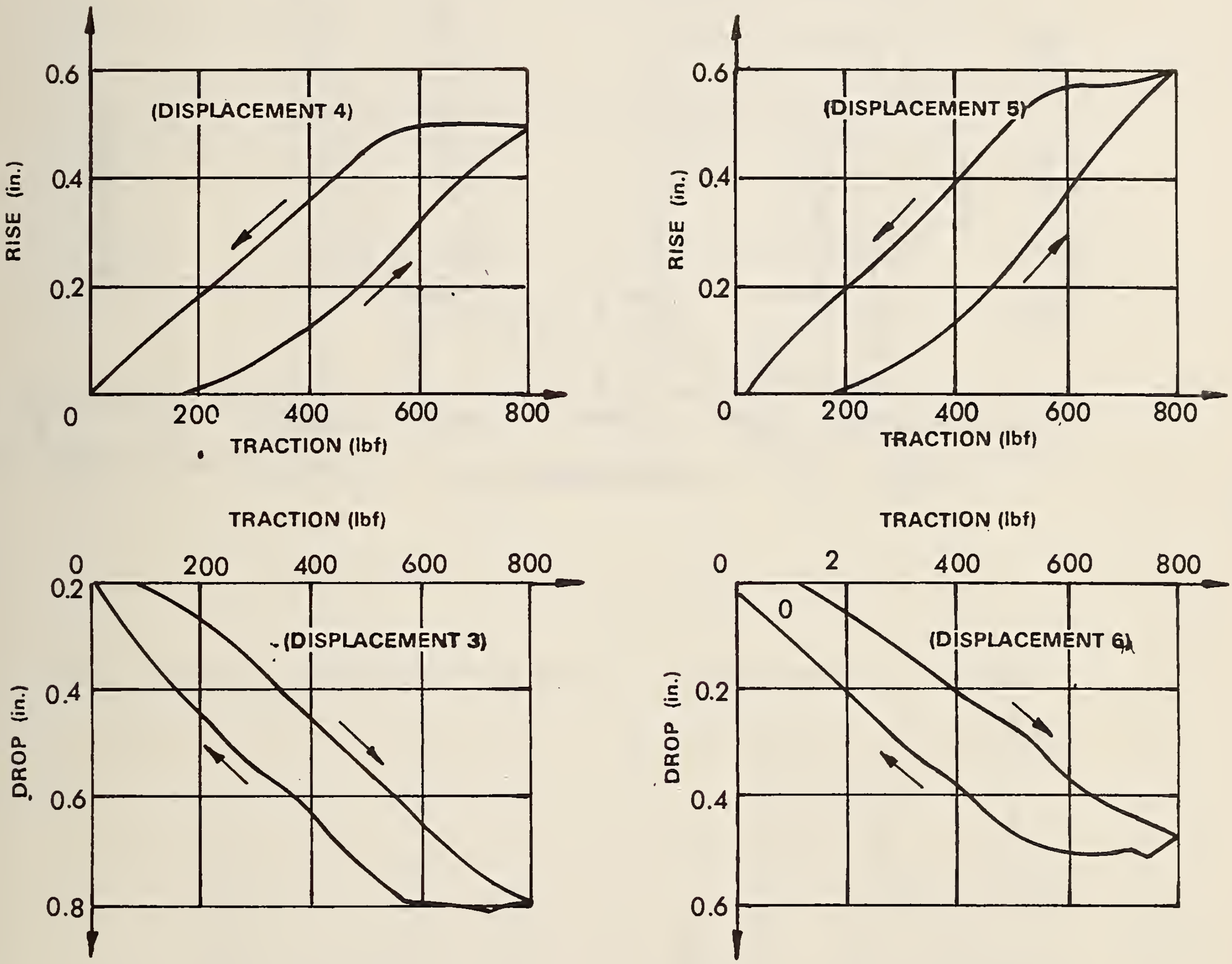


Figure 14. Displacements associated with roll and pitch.

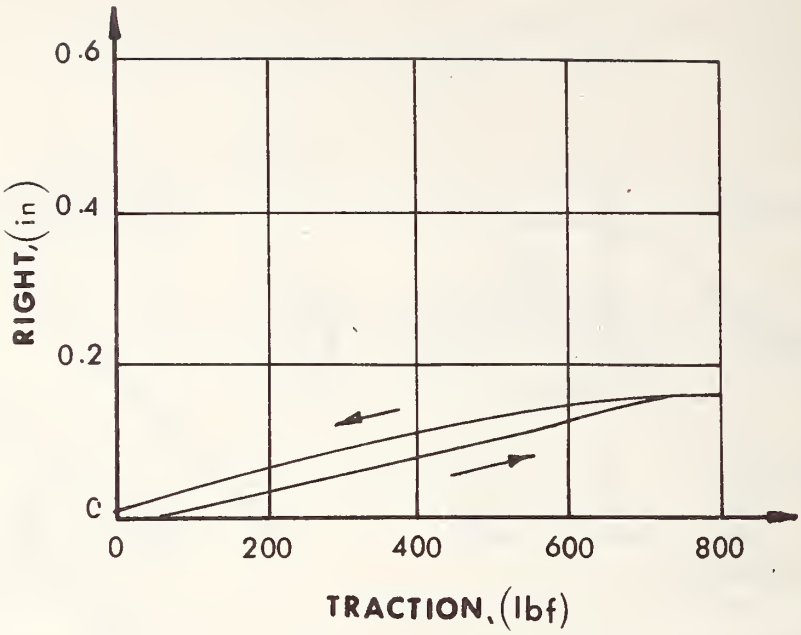


Figure 15. Displacement of location 2 with change in traction force.

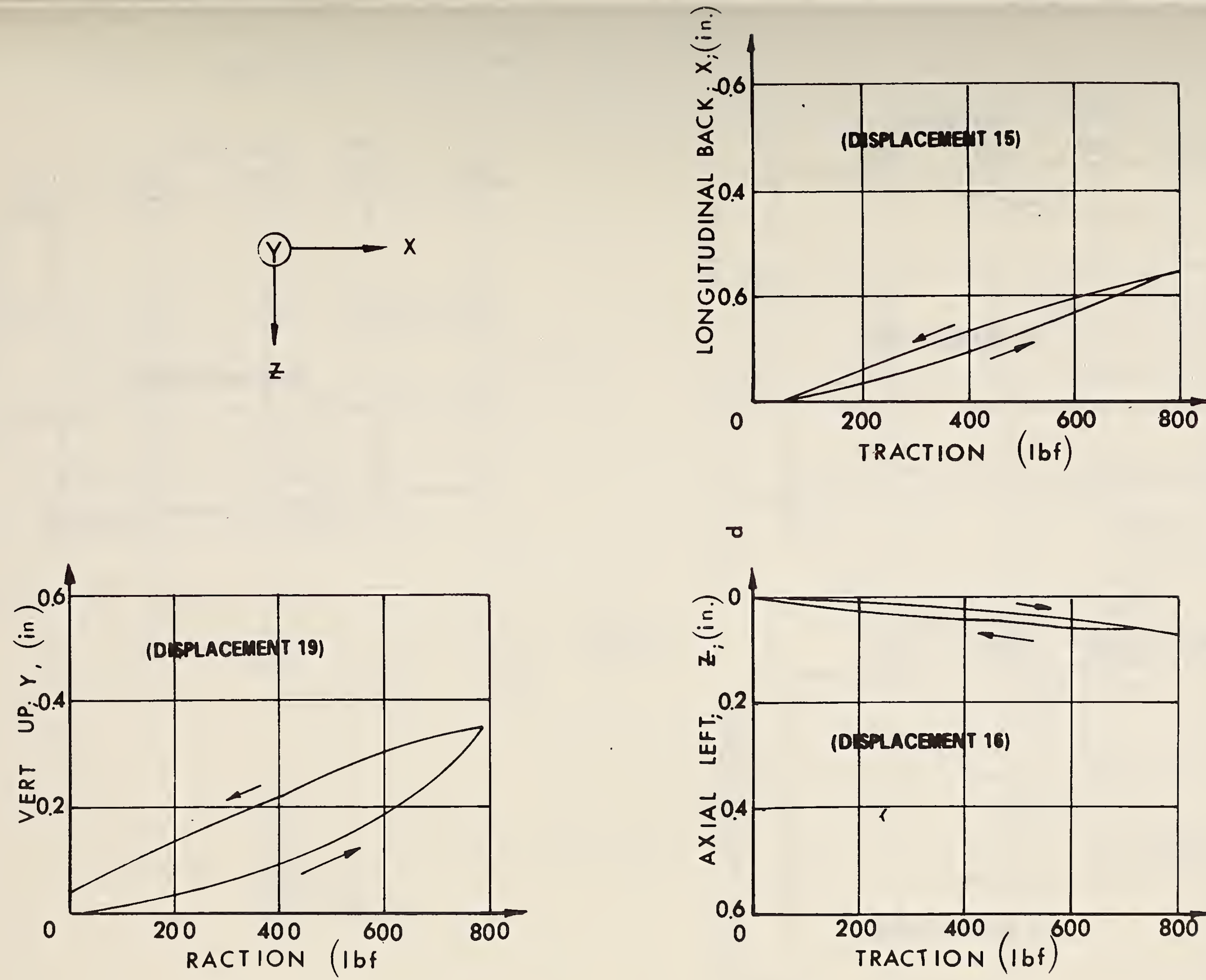


Figure 16. Displacement of the hitch.

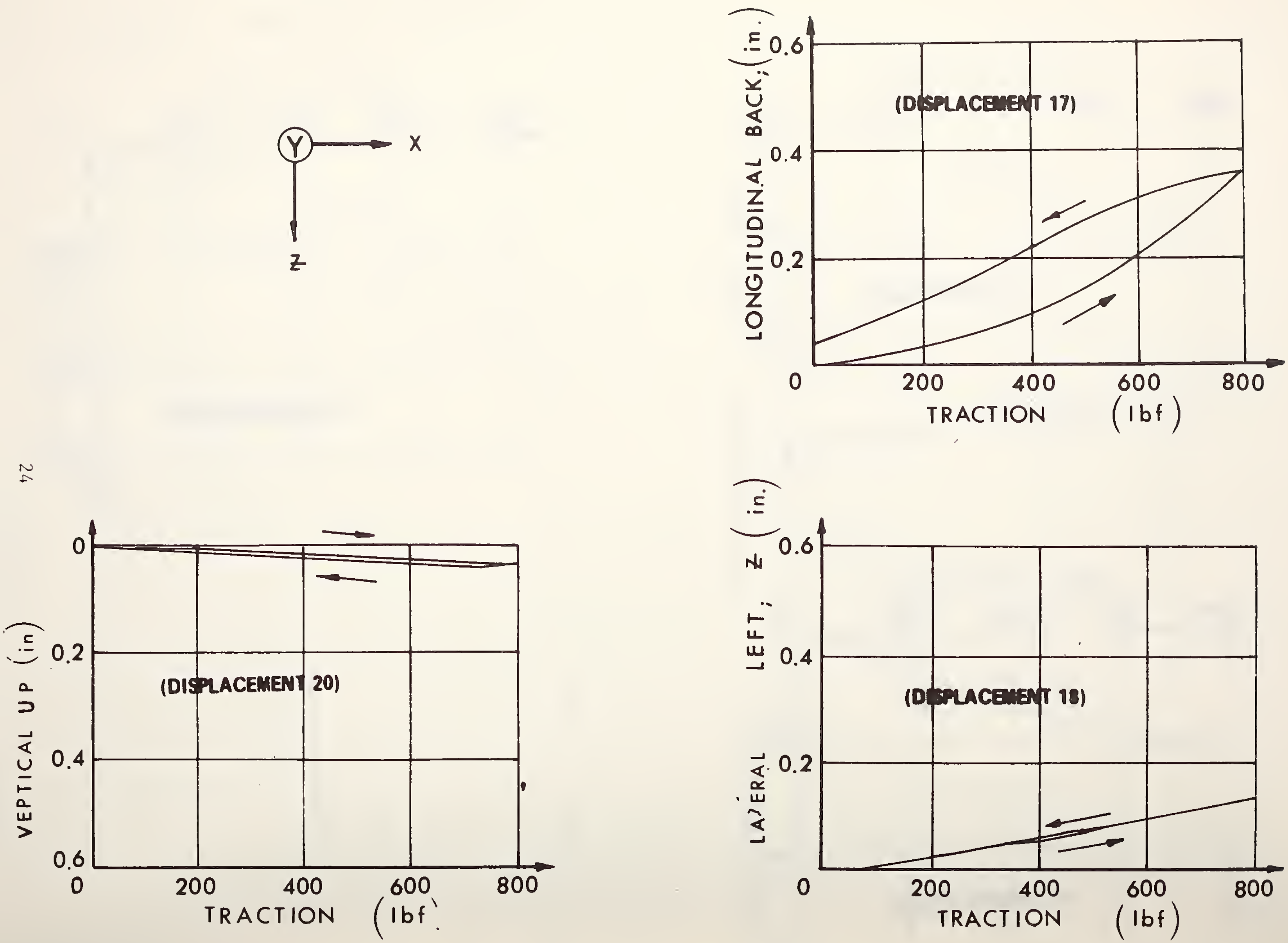


Figure 17. Displacement of the tow vehicle rear axle.

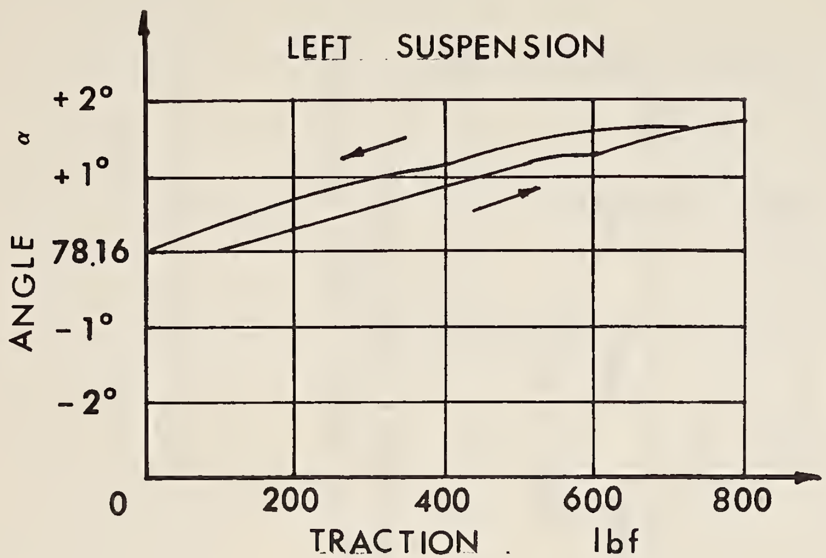


Figure 18. Rotation of the left parallelogram suspension.

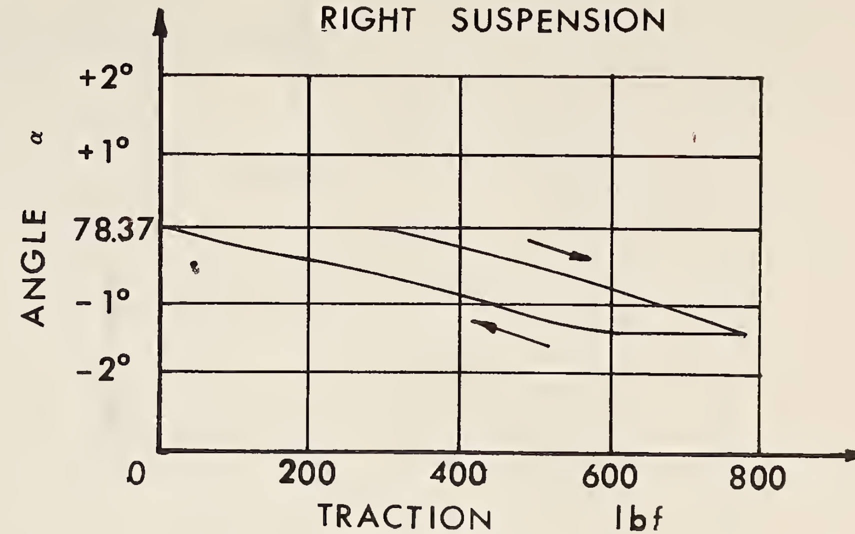


Figure 19. Rotation of the right parallelogram suspension.

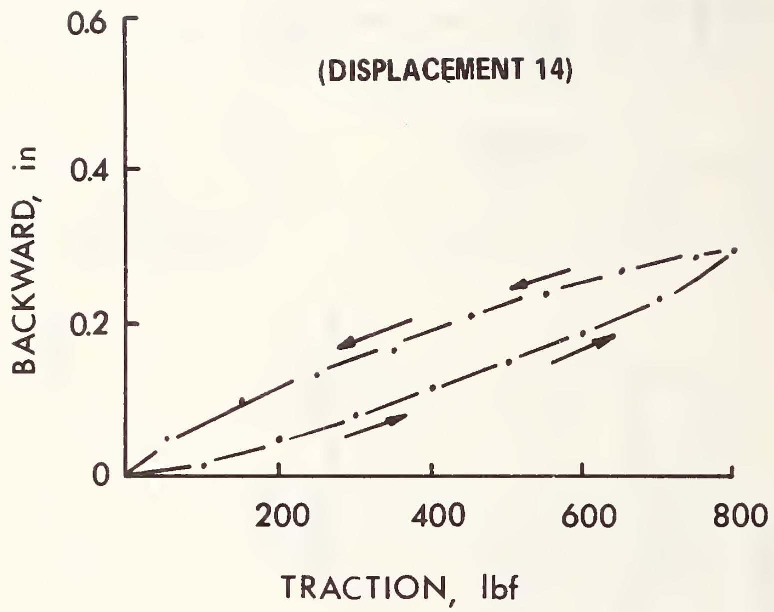


Figure 20. Displacement of the force plate with respect to the axle.

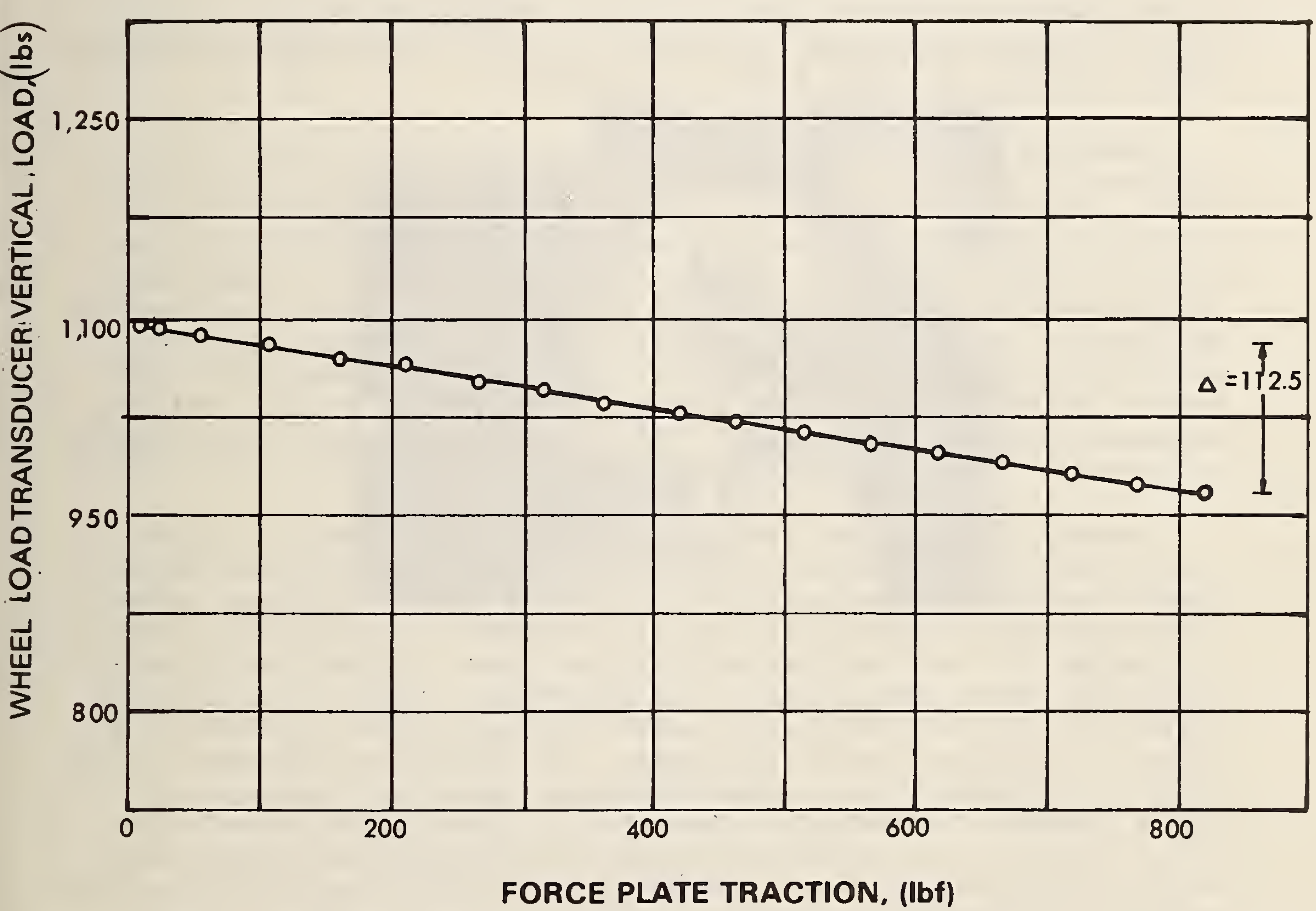


Figure 21. Vertical force sustained by the test wheel.

To experimentally confirm equation 1, both trailer wheels were supported on an air bearing and lateral force, F_{WR_z}, was measured with a load cell. The experimental setup is shown in figure 22 and the test results are given in figure 23. There was no traction force applied at the free wheel. The lateral force increased proportionately with an increase in horizontal traction force. Rewriting equation 1 and using T = 64 inches and L = 120 inches,

$$\frac{F_{WR_z}}{F_{WL_x}} = \frac{T}{2L} = \frac{64}{2(120)} = \frac{1}{3.75}$$

At 800 pounds traction the axial force was measured to be 210 pounds. These values are equivalent to a ratio of 1/3.81. The theory and experimental verification agree within 1.6 percent.

Equation 7 indicates that the vertical force on the left wheel decreases as the horizontal traction force increases. To verify this result, the vertical load on the force plate was recorded while the horizontal traction force was increased. The experimental results are given in figure 21. The initial load was 1092.5 pounds. (Additional fixtures and dial gages weighing 7.5 pounds affected that force plate at this time.) As the traction force was increased to 800 pounds, the vertical load declined to 980 pounds. For H = 14.7 inches and L = 120 inches, the theoretical change in vertical load is 98 pounds, while the measured value was 112.5 pounds. The theory and experiment agree within 15 percent.

Equation 10 indicates that the vertical force on the free tire remains constant as the traction force is increased. To verify this result the vertical load on the free tire was measured by means of an air-bearing force plate while the traction force was applied to the test tire by means of another air-bearing force plate. Lateral force was restrained at the trailer axle. The experimental results are given in figure 24. The vertical force remained constant within 5 pounds for a change in traction force of 800 pounds. The theory and experiment agree within 0.6 percent. To evaluate the change caused by floating both wheels instead of allowing the free wheel to shear under lateral force, the air supply to the force plate under the free wheel was interrupted. The test was repeated, hence, the second trace, with the result that the vertical load remained constant but shifted by two pounds as shown in figure 24.

2.3. Discussion

It has been shown that the traction force generates a lateral force which displaces the axle in the direction of the free tire and places the free tire in shear (fig. 8). With no traction force present on the free tire, the axle displaces outward (fig. 6) shearing the tire and shortening the wheel radius (fig. 8). At a point on the hub, outward

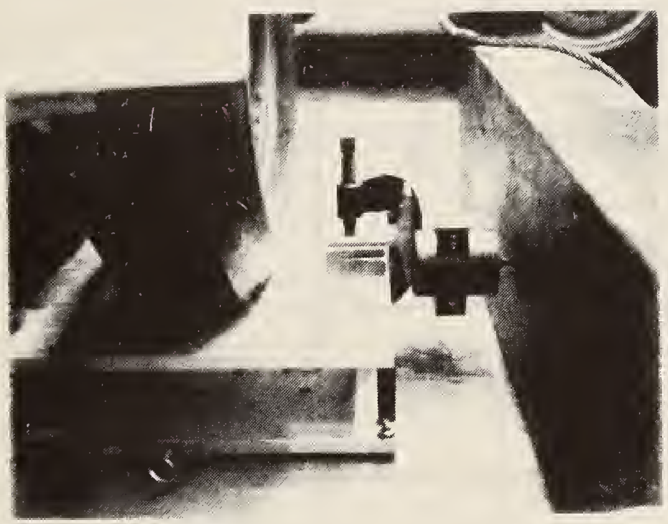


Figure 22. Lateral force test setup.

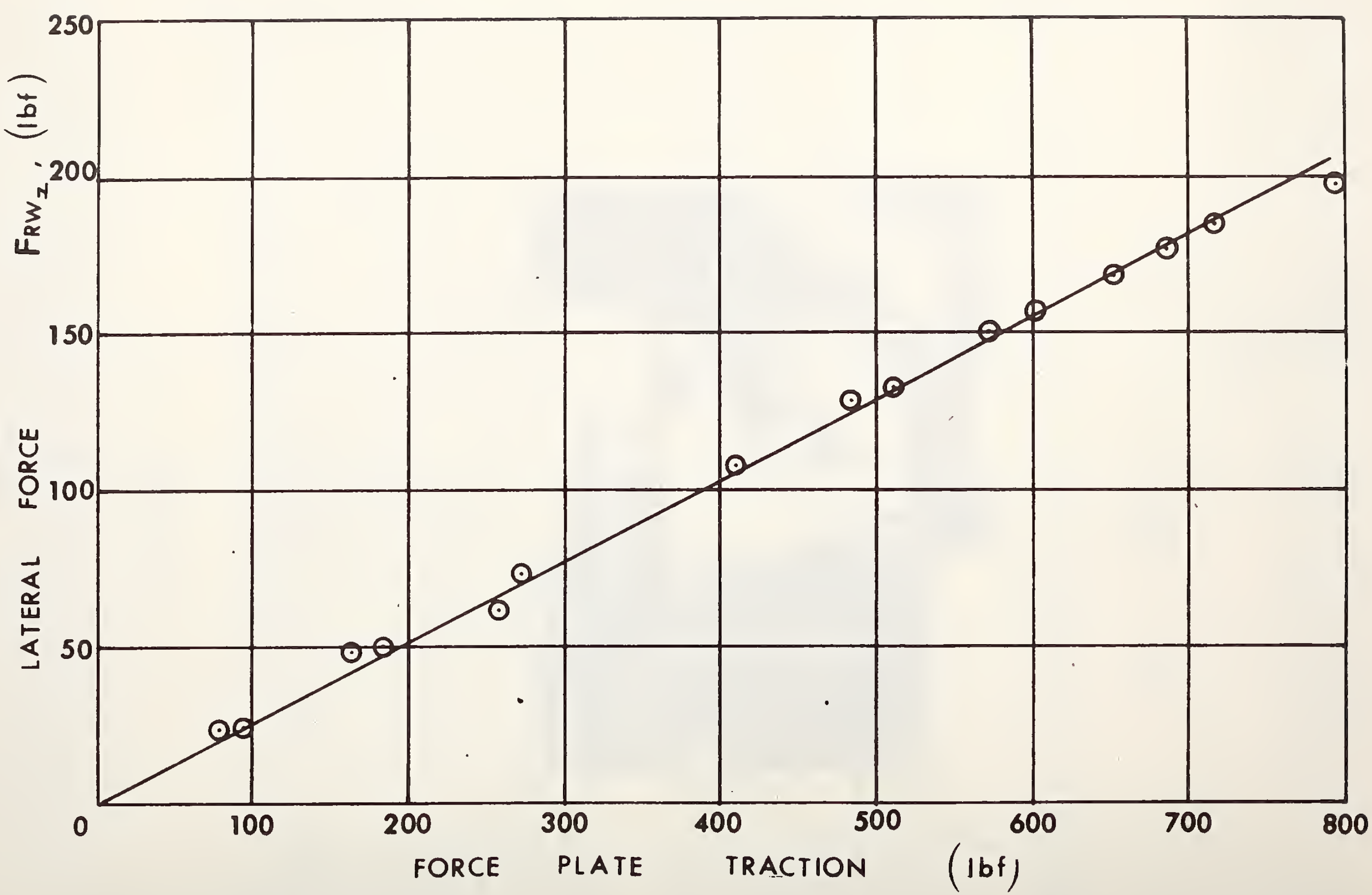


Figure 23. Lateral force measurements.

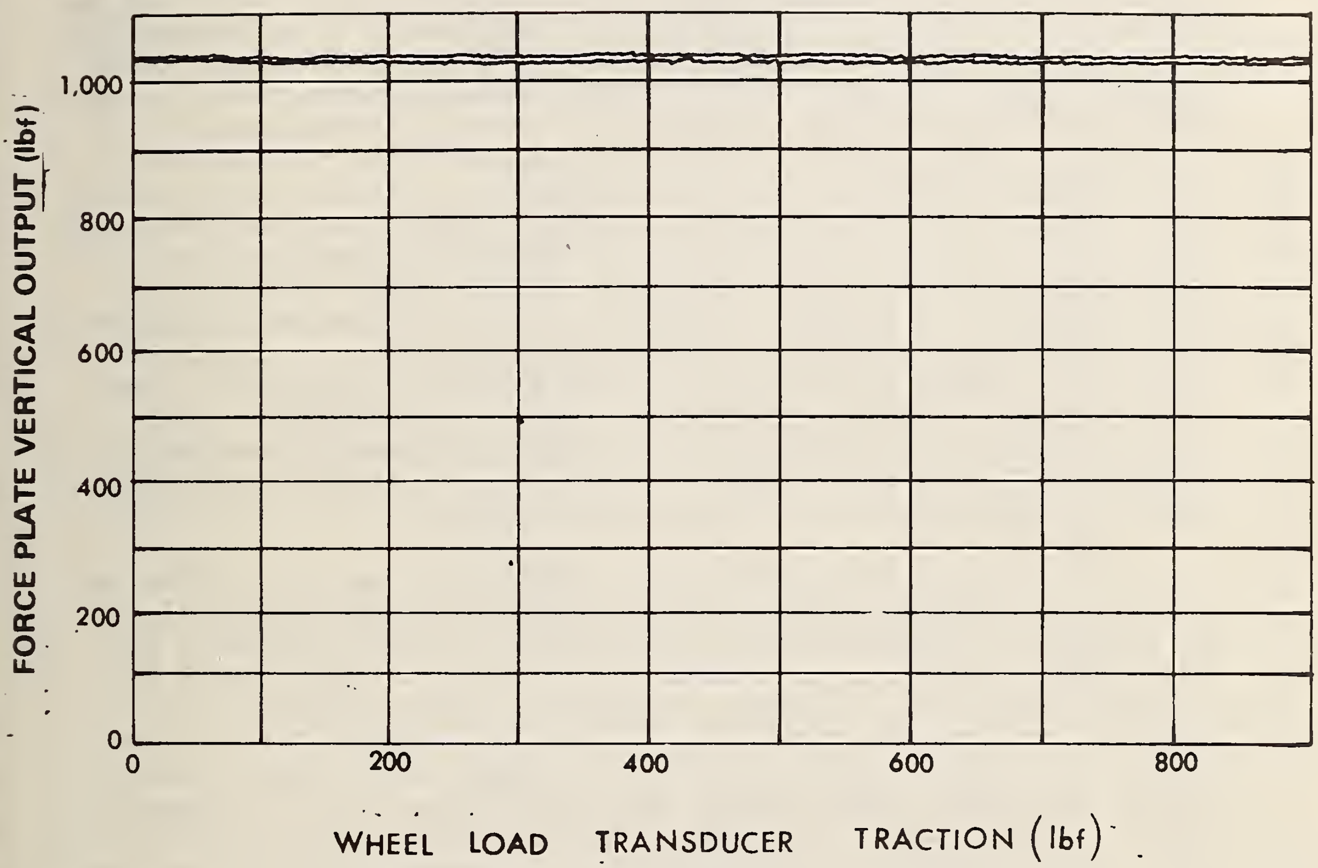


Figure 24. Vertical force sustained by the free wheel.

of the free wheel, the axle moves slightly forward (fig. 12). Simultaneously, the test wheel is moving rearward (fig. 13) and due to the reduction in vertical load, the test wheel radius increases (fig. 11).

The motion of the skid trailer axle consists of a lateral displacement toward the free wheel, a rolling of the axle due to the additive effects of the changes in both wheel radii, and a yawing of the axle. The axle yaw angle constitutes a steering angle and tends to steer the skid trailer out of the tow vehicle trajectory.

While the equations given apply to the external forces acting on the skid trailer, a computer program is being developed to study the internal forces acting on the skid trailer components. It is interesting to note that the trailer rolls downward at the test wheel, while the vertical load on the test wheel is being reduced, implying that the suspension spring is required to support more vertical force when the traction is applied than when it is not. A portion of the numerical results from the program are given in figure 25. All the forces acting on the component of the suspension system of figure 3 are not given. As shown, the force sustained by the spring on the test wheel side increases while the force sustained by the spring on the free rolling wheel decreases. The nominal spring rate of the suspension springs was measured as 460 pounds/inch. By reviewing figure 16 for a traction force of 400 pounds and using the trailer dimensions, the roll of the trailer nominally agrees with the computer program solution. This result is also in agreement with the measured rotations of the parallelogram linkages (figs. 18 and 19). The pitching of the trailer is nominal compared with the rolling of the trailer.

The horizontal force developed at the hitch is resisted by the tow vehicle. In a similar manner to that described for the skid trailer, the tow vehicle suspension and the tow vehicle tire are subjected to a shear force. The hitch is displaced laterally 0.25 inches toward the test wheel side (fig. 16) while the axle also moves laterally 0.12 inches in the same direction (fig. 17) when the traction force is 800 pounds. This would indicate that the horizontal spring rate of the tow vehicle suspension system and the shear spring rate of the tow vehicle tire are about equal since the deflections are equal under the same force. These results apply to the case of no water load. The vertical spring rate of the tow vehicle suspension is non-linear with load (fig. 39). The horizontal spring rate may also depend on the water load. While the magnitudes of the hitch forces depend on the trailer dimensions, notice that the magnitudes of the yaw displacements depend on the spring rate of the tow vehicle, the spring rate of the tow vehicle tires, and the spring rate of the trailer free tire (fig. 26).

The horizontal traction force develops a longitudinal force at the hitch which is resisted by the tow vehicle. It is shown in figures 16 and 17 that this force resulted in the same displacement of the rear axle as occurs at the hitch. Consequently, the longitudinal spring rate

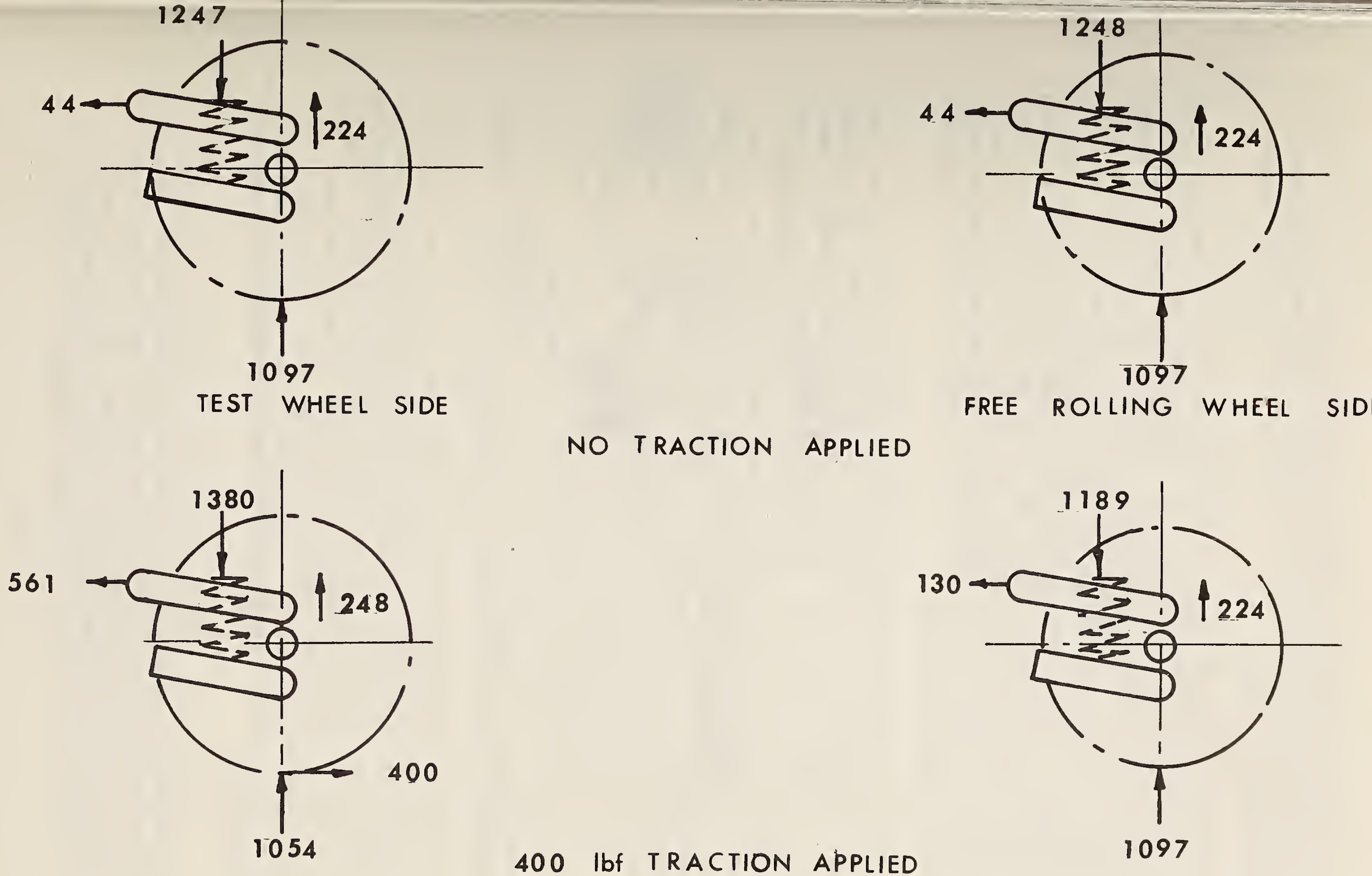


Figure 25. Suspension forces, lbf, given by computer program.

of the tow vehicle suspension is quite high with respect to the longitudinal spring rate of the tow vehicle tires. Thus, the properties of the tow vehicle tires determine, to a great degree, the longitudinal displacement of the hitch.

The instant center of axle yaw rotation is about the laterally displaced footprint of the free tire. The trailer body yaw displacements are shown in figure 26a as displacement vectors in the horizontal plane. Each vector is identified by the system component which influences the displacement the most. It is interesting to note how much the yaw rotation of a given trailer depends on the tow vehicle and free tire characteristics. Figure 26b indicates the changes in the instant center location which correspond to changes in tow vehicle and tire characteristics. As the spring rate of the tow vehicle suspension and the tow vehicle tires are made stiffer, the instant center of yaw rotation moves further from the trailer so the trailer body rotates through a smaller angle for the same hitch forces.

The trailer suspension design does determine the axle angular rotation which accompanies the trailer body rotation. The FHWA IRS trailer axle rotation is nominally 2.5 times the body rotation. We do not want the trailer to steer out of the tow vehicle trajectory, so we would not want the axle to yaw. However, provision must be made for some axle yawing so the trailer can make turns without scuffing the tires. The trailer axle yaw should not be a large multiple of the trailer body yaw. This ratio may be considered a figure-of-merit for the trailer suspension system design. If the trailer is required to negotiate turns without scuffing the trailer tires, the ratio must be greater than one. It is interesting to note that if the trailer axle was rigidly mounted in the trailer body, the axle would still rotate due to the characteristics of the tow vehicle and the tires of both vehicles. The associated scuffing might cloud the skid resistance measurement.

The trailer body pitches downward at the hitch due to the transfer of vertical force from the test wheel to the hitch.

The foregoing paragraphs describe the motions of the trailer and tow vehicle which occur under increasing and decreasing traction force. These movements are related to the changes in the external forces acting on the trailer and tow vehicle system which accompany the application of a traction force at the tire-pavement interface. A set of mathematical equations relating the system motions to the traction force would constitute a "transfer function." Knowledge of the transfer function is required to understand the relation of the wheel transducer output to the traction force.

It is suggested that similar displacement measurements be made on other skid measuring systems and that the motions also be correlated with the change in external forces which accompany the application of lateral force to better understand the measuring systems. In the following sections it will be shown that the application of this knowledge to the calibration process can control and reduce measurement differences.

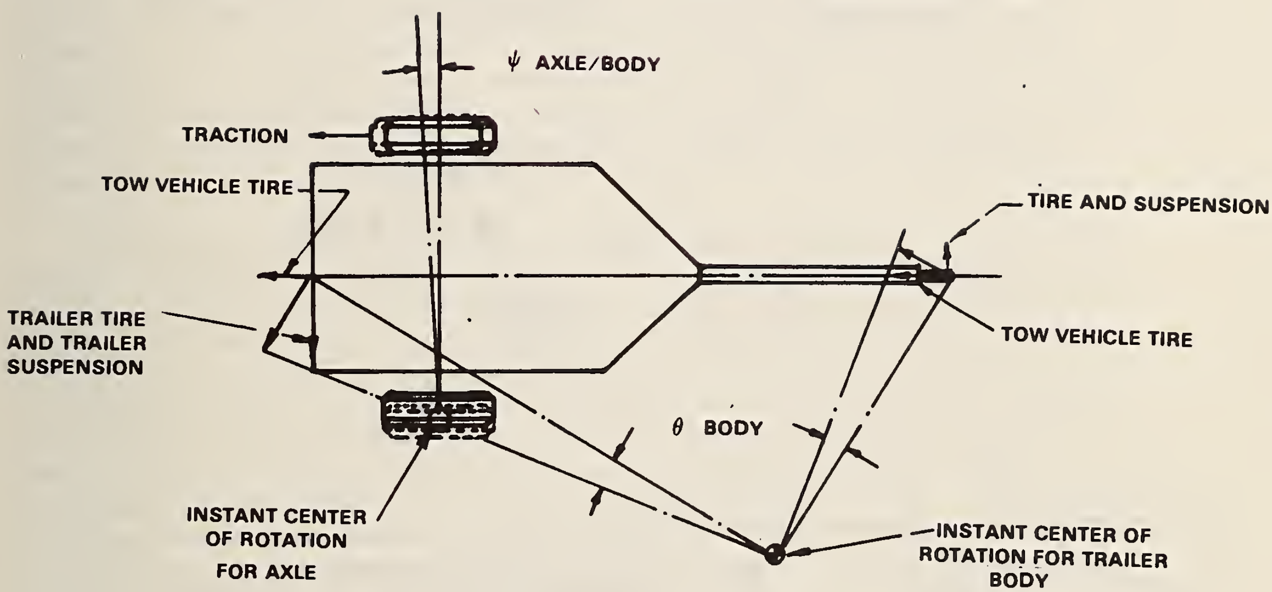
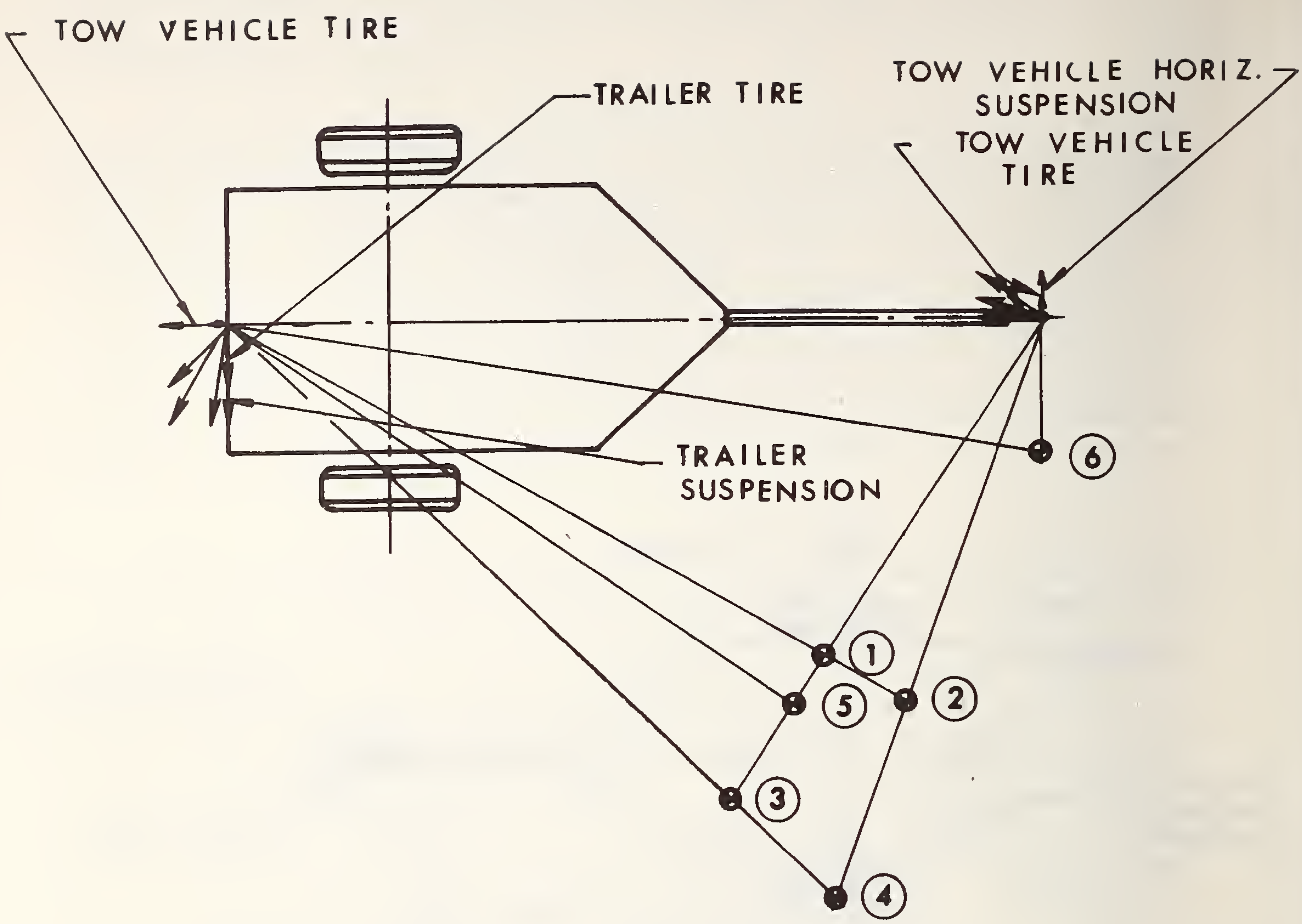


Figure 26a. Trailer body yaw displacement vectors.



Instant center	Condition	Displacements			
		Tow vehicle		Trailer	
		Tire percent	Horizontal suspension percent	Tire percent	Suspension percent
1	Normal	100	100	100	100
2	Stronger tow vehicle suspension	100	0	100	100
3	Stronger tow vehicle tire	0	100	100	100
4	2 and 3 combined	0	0	100	100
5	Stronger trailer tire	100	100	0	100
6	Stronger trailer suspension	100	100	100	0

Figure 26b. Effect of tow vehicle and tires on yaw instant centers.

3. THE WHEEL TRANSDUCER AS A DETECTOR OF SKID RESISTANCE

The skid resistance to be measured occurs at the tire-pavement interface. For practical reasons, the wheel load transducer is located on the axle away from the point of application of the force. While a simple traction force is applied to the system by means of a force plate (sec. 4) the force at the tire-pavement interface also includes vertical and lateral components. The distributed forces at the tire-pavement interface may be viewed as a general force of three rectangular components acting at an effective footprint. The effective footprint moves with changes in the tire characteristics [1]*.

When a force is translated to a parallel position in space, while maintaning rigid-body equivalence, a couple-moment is simultaneously generated. Since the transducer is located on the axle, remote from the force, the transducer is subjected to both generalized force and a generated moment. The moment can also be resolved into rectangular components so that the load on the transducer consists of three force components and three moment components. The weight of the wheel and components located between the footprint and the transducer are additional forces applied to the transducer during a static calibration. Dynamic and inertial forces also act on the transducer during use.

The characteristics of the tow vehicle and trailer influence the vertical component and the lateral component of the generalized force acting in the tire-pavement interface. Also these characteristics influence the movement of the transducer with respect to the effective footprint. By calibrating the transducer while it is installed in the trailer and while the trailer is attached to the tow vehicle some of these variables are taken into account. However, the calibration equipment to be described is subjected to the varying external forces accompanying the application of the input traction force. The calibration equipment too, has a transfer function which depends on the characteristics of the system with which it is used. From a knowledge of the output from the calibration equipment alone, it is impossible to distinguish between a change in the traction force and a change in the transfer function of the calibration equipment occuring under different load conditions. The wheel load transducer is calibrated under varying force conditions which depend on the method of using the trailer. There is a need to calibrate the calibration equipment under the same varying force conditions, as will be discussed in succeeding sections.

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*Numerals in brackets denote the literature references cited at the end of this report.

3.1. The Effect of System Variables on Skid Number

The skid resistance of paved surfaces measured in accordance with the ASTM method E 274-70 is given in terms of skid numbers (SN) where

$$SN = \frac{F_{WL_x}}{F_{WL_y}} \quad x \quad 100$$

For trailers where F_{WL_y} is not measured directly, wheel load reduction is taken into account by means of equation 7, and equation 8 is used to calculate the skid number:

$$SN = \frac{F_{WL_x}}{F_{WL_{yo}} - F_{WL_x}\left(\frac{H}{L}\right)} \quad x \quad 100 \quad . \tag{8}$$

Paragraph 1.2 of the ASTM method states:

> "The method utilizes a measurement representing the steady state friction force on a locked test wheel as it is dragged over a wetted pavement surface under constant load and at a constant speed while its major plane is parallel to its direction of motion and perpendicular to the pavement."

The yaw angle of the axle tends to steer the trailer on a trajectory such that the test tire's major plane is not necessarily parallel to its direction of motion.

3.1.1. Hitch Height Variation

Many of the variables are related to a change in hitch height, leading to rotation of the wheel transducer. In some cases the effects are additive. The change in skid number for a change in hitch height with the other values remaining constant is

$$\frac{\partial(SN)}{\partial H} = \frac{\frac{F_{WL_x}^2}{L} \qquad (100)}{\left[F_{WL_{yo}} - F_{WL_x}\left(\frac{H}{L}\right)\right]^2} \quad ,$$

therefore,

$$\partial(SN) = \frac{(SN)^2 \quad \partial H}{100L} \quad .$$

For a skid trailer with an L dimension of 120 inches, and measuring a skid number of 50, for a one inch change in hitch height, the change in SN is

$$\partial SN = \frac{(50)^2}{(120)} \quad \frac{(1)}{(100)} \approx 0.2$$

$$\frac{\partial SN}{SN} = \frac{0.2}{50} = 0.4\%$$

The change in hitch height also results in a change of vertical wheel load. Using equation 7,

$$\frac{\partial F_{WL_y}}{\partial H} = -\frac{F_{WL_x}}{L} .$$

When F_{WL_x} = 800 pounds, the vertical load is further reduced 6-2/3 pounds for a one inch change in hitch height. Since the vertical load is nominally 1000 pounds the additional change with a one inch change in hitch height is 2/3 percent.

3.1.2. Hitch-to-Axle Length Variation

The footprint displacement consists of the movement of the force plate with respect to the axle plus the backward motion of the axle which is approximately one inch at 800 pounds traction. (SN=80) Taking the partial derivative of equation 8 again,

$$\frac{\partial (SN)}{\partial L} = \frac{\dfrac{-F_{WL_x}^{\;2}\; H}{L^2}}{\left[F_{WL_{yo}} - F_{WL_x}\left(\dfrac{H}{L}\right)\right]^2} ,$$

and

$$\frac{\partial (SN)}{\partial L} = \frac{-(SN)^2}{100} \; \frac{H}{L^2} .$$

For a trailer with L and H dimensions of 120 and 12.9 inches respectively, measuring a SN of 80 the change in SN is

$$\partial SN = \frac{-(80)^2(12.9)}{(100)(120)^2} = -0.057$$

$$\frac{\partial SN}{SN} = \frac{-0.057}{80} = -0.07\%$$

This same change in vertical load occurs at the hitch but in the opposite direction.

4. STATIC CALIBRATION OF THE WHEEL TRANSDUCER INSTRUMENTATION USING A FORCE PLATE

An air-bearing force plate is used to apply a traction force to the trailer at the tire-pavement interface, during a static calibration of the wheel transducer. In this section, the force plate and the fixture for calibrating the force plate are described.

The force plate has two outputs, vertical load and horizontal traction. Strain gages are mounted on internal beams such that the beams bend in a vertical plane when a vertical load is present on the plate and the beams bend in a horizontal plane when a horizontal traction force is applied to the plate. The force plate in use with a skid trailer is shown in figure 27. The force plate is placed underneath the test tire on the air-bearing platform. Adjustable flow valves are utilized to level the unit by distributing the incoming air to the air bearings. The traction force is applied through the chain.

4.1. The Importance of Procedure in Calibration of the Force Plate

In this section, the force plate variables are identified. Their relative importance in a specific application depends on the method of using the force plate and the principles of design employed in the force plate. These variables affect the results and should be considered when developing the calibration procedures. Two force plates were studied; a commercial air-bearing force plate used with the FHWA IRS and a modified commercial unit of another type, used by a state highway department. It will be shown that a "small" shop error made during the modification of the state unit resulted in erratic operation. The occurrence of the error may be considered fortunate since it led to examples for discussion which detail the merits of calibrating the force plate under conditions of combined loading and force plate mechanism movement which occur in use.

It is important to identify the crosstalk differences, nonlinearities, and hysteresis loops present in the force plate output. Otherwise, when the force plate is used to calibrate a wheel transducer, in an accounting of the errors, differences applicable to the force plate will be charged to the wheel transducer.

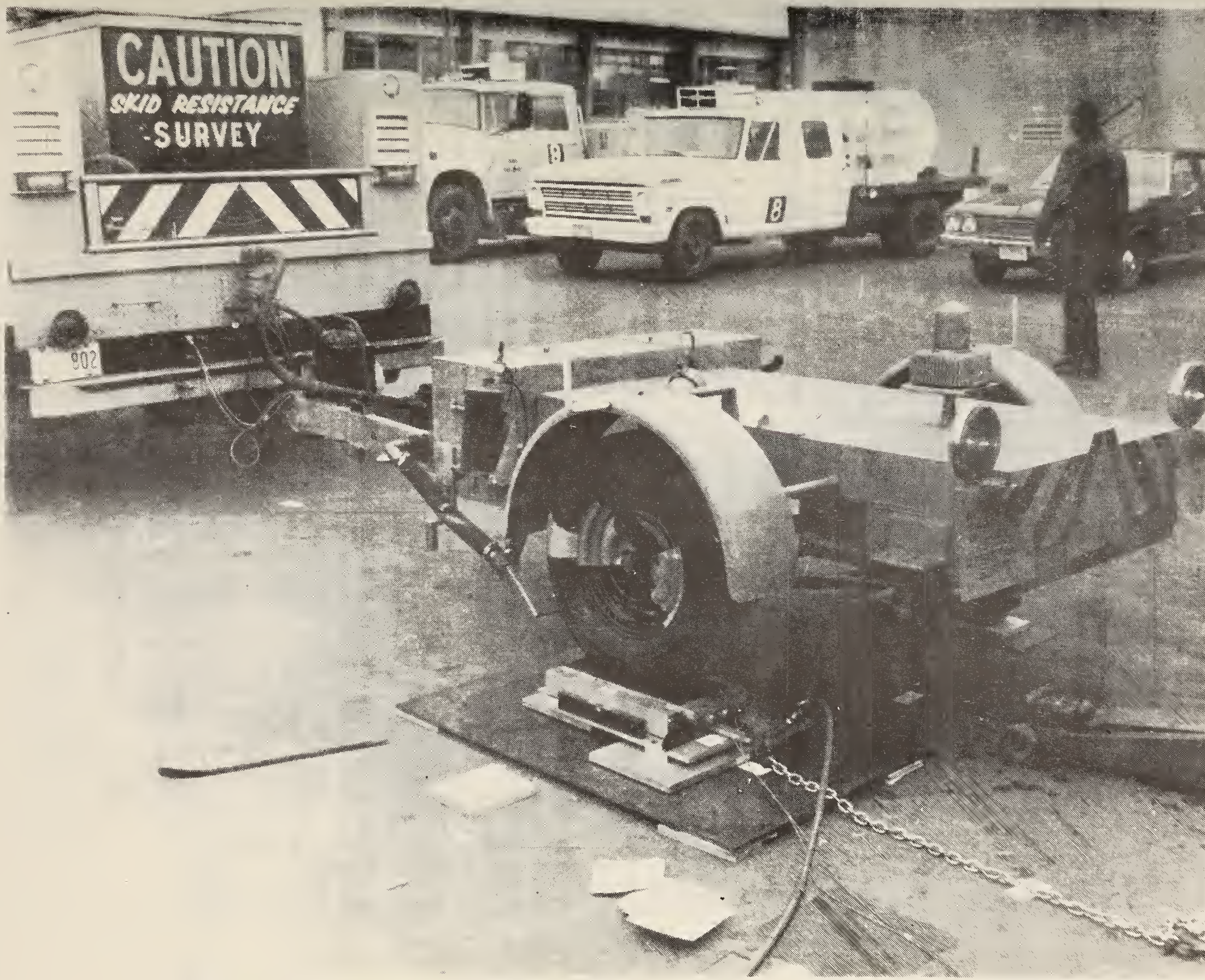


Figure 27. Use of the force plate.

While using the modified state force plate to calibrate the interim reference skid trailer an example of this occurred. The procedure recommended for calibration of the force plate utilized an external load cell. When the screw mechanism was turned, force was applied to the internal and external load cells but without significant movements of the force plate mechanism. The force plate calibration curve was quite linear. When the force plate was then used to calibrate the wheel transducer the results were as shown in figure 28. The calibration curve indicates a 70 pound hysteresis loop width at a traction force of 350 pounds. That something was wrong became evident when a review of the results showed that the wheel transducer output corresponded to more force than was indicated as being applied by the force plate.

In attempting to identify the discrepancy the modified state force plate was mounted above the IRS force plate, which in turn was mounted on its air-bearing platform. The test was conducted without movement of the state force plate mechanism with the result shown in figure 29. The output was more linear with only a small hysteresis loop evident. This result led to an inspection of the mechanism which revealed a machining error in the modification. The error was corrected and a calibration test conducted again with the result shown in figure 30.

The manufacturer of the state force plate recommends that a vibration be applied to the force plate by hitting the tire with a heavy rubber mallet at each static loading before a record of the readings is made. These results were obtained without the vibration since further testing indicated the vibration increased the scatter of the data because the direction of the Coulomb friction force was random.

The test results of the wheel load transducer output versus state force plate traction output are given in figure 28 when rotation of the screw mechamism of the state force plate occurred and in figure 29 when rotation of the screw mechanism did not occur. The differences are due to the mechanism movement which was made abnormal by the modification error in machining. What is important here is that the procedure used to calibrate the state force plate did not require movement of the mechanism through the 1.1 inch displacement occurring during an IRS transducer traction calibration test. Consequently, the modification error was not identified during the state force plate calibration. Poor results later would normally be charged to the wheel transducer rather than the force plate.

It is clear that the force plate should be calibrated under the conditions of use. Specifically,

a) The movement of the internal mechanism must be equal to or greater than that which occurs during use.

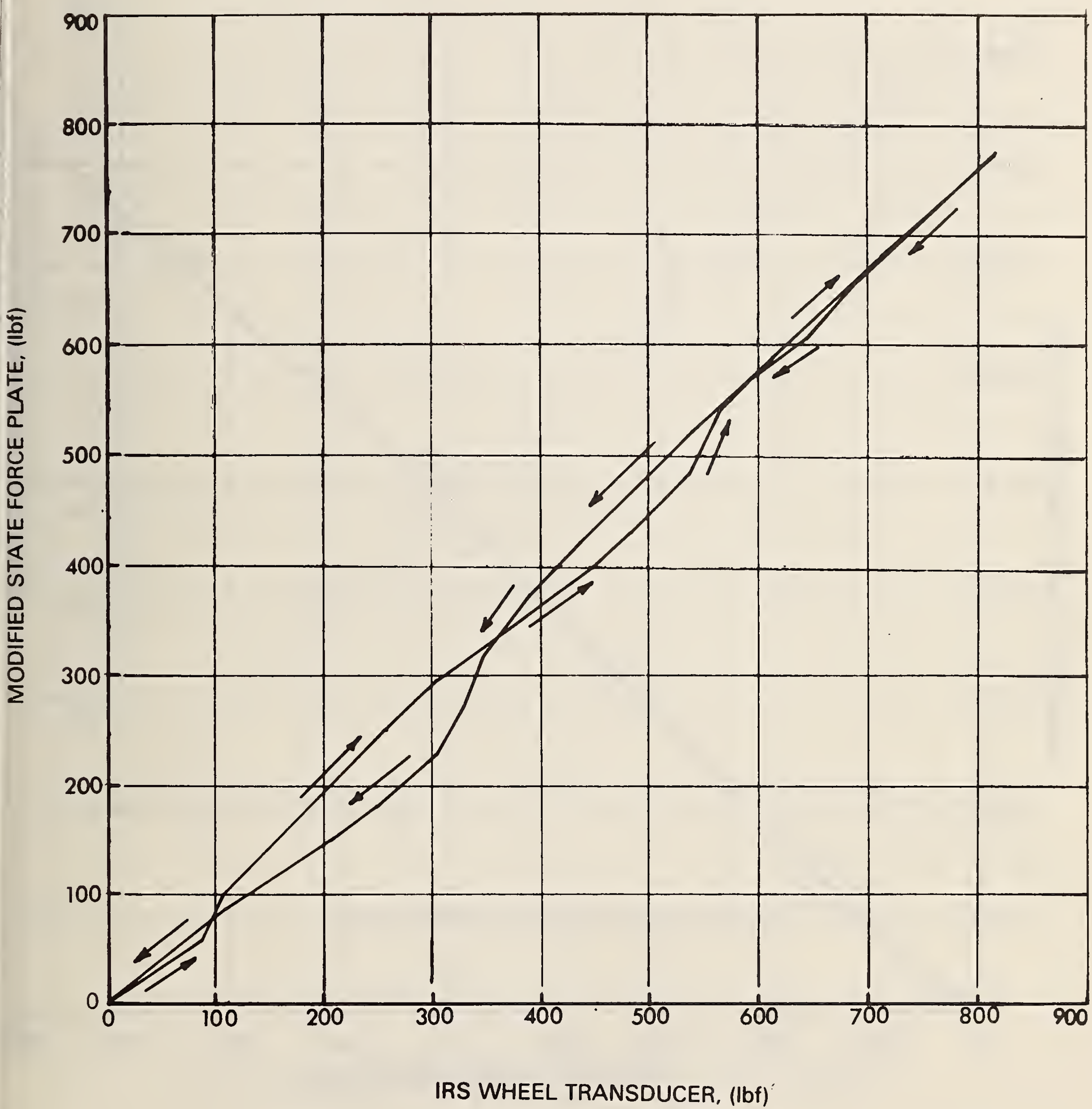


Figure 28. IRS wheel transducer calibrated with modified state force plate.

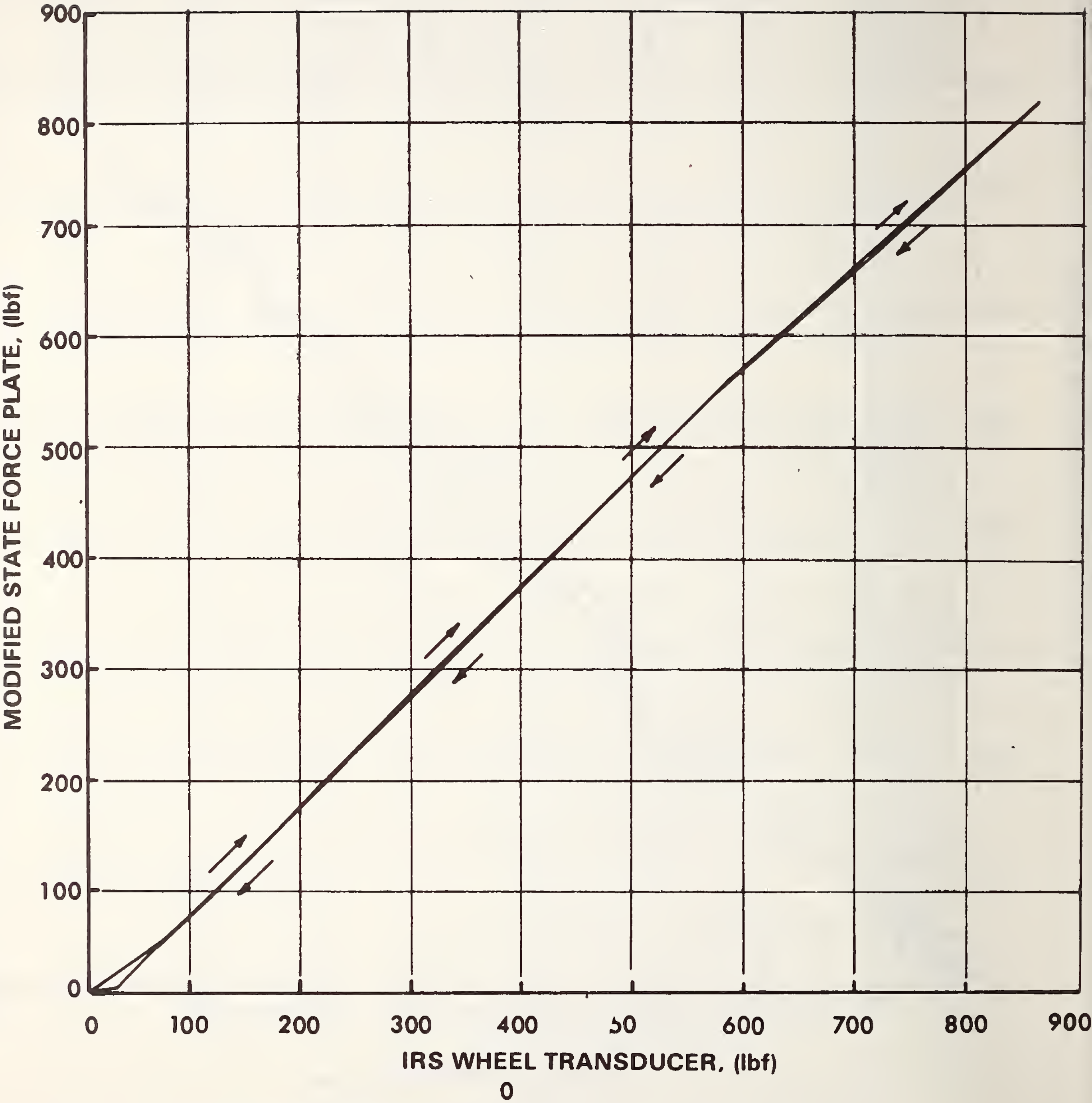


Figure 29. IRS wheel transducer calibrated with movement eliminated in the mechanism of the modified state force plate.

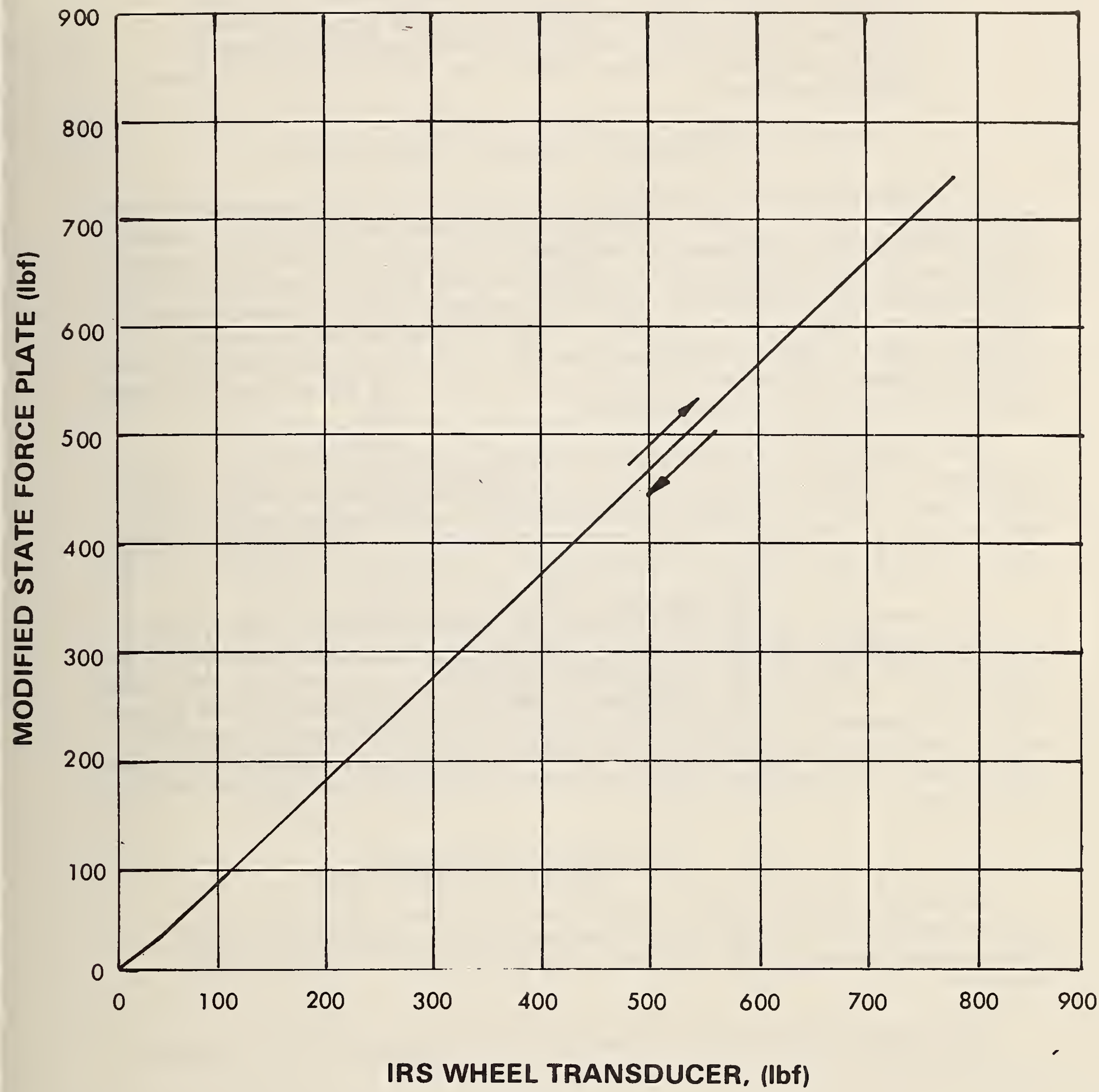


Figure 30. IRS wheel transducer calibrated with modified state force plate with normal movement of the force plate mechanism, after correction of a machining error.

b) The force plate must be subjected simultaneously to the external forces which are applied during use. If these external forces vary, they should vary during calibration or at least fixed forces which bound the variation in force should be used.

4.1.1. Positioning the Load on the Force Plate

The output of the force plate is influenced by the location of the vertical load on the plate. The IRS force plate was mounted in a dead-weight machine and subjected to different vertical loads at the seven locations shown in figure 31. Digital printed outputs from the vertical load channel were obtained by means of automatic signal conditioning equipment and are given in table 2. This is the variation due to a uniaxial load. Under a combined load the presence of the traction force would increase the variation (see sec. 4.1.3). The scale factor of the output readings shown is arbitrary.

The modified state force plate is shown in figure 32. The moving platform is supported by six roller bearings and moved by means of an Acme screw. The force plate contains a load cell between the platform and its drive. The drive speed is made continuous and variable by means of an electric motor and its control.

The manufacturer recommends that the platform be positioned over only four bearings during a test. Since the bearings are stationary the vertical load changes in location with respect to the bearings as a test progresses. If the load is initially placed at the center of the platform, the support can change from one set of four bearings to another set of four bearings, changing the loading conditions, consequently, the manufacturer's directions lead to an off-center location for the vertical load.

4.1.2. The Combined Load Problem

During the force plate calibration of a wheel transducer, the forces change in accordance with the equations developed in section 2. The vertical force at the test wheel is reduced in accordance with equation 7.

The total lateral force shared by the two trailer wheels is given in equation 1:

$$F_{WR_Z} = (F_{WL_x} - F_{WR_x}) \frac{T}{2L} \quad .$$

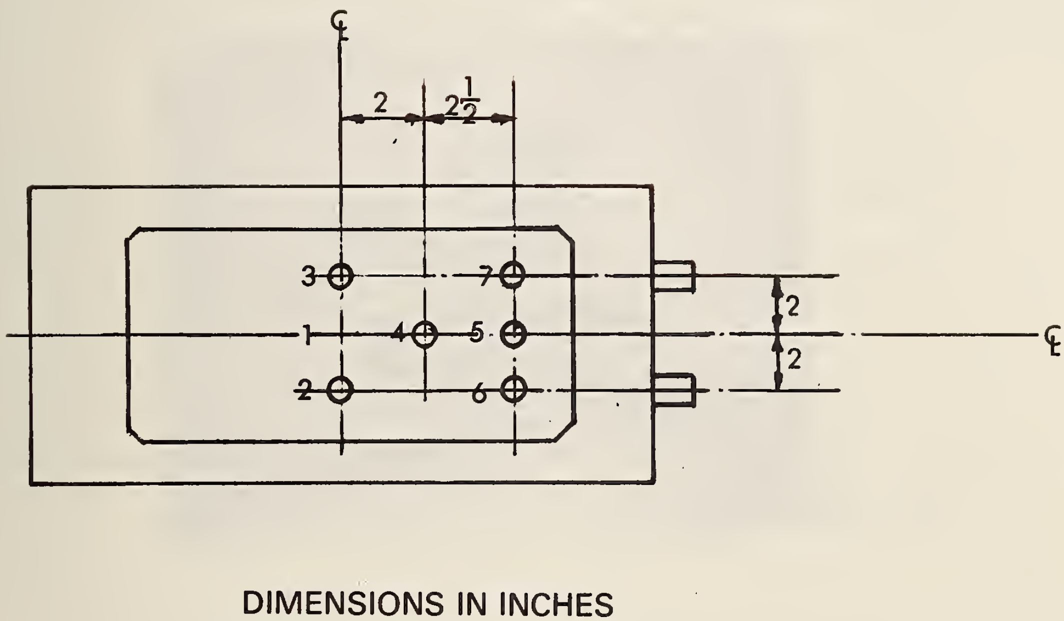


Figure 31. Locations of vertical test loads applied to the IRS force plate.

Table 2. Variation of IRS force plate vertical output due to position of vertical test load

Vertical load	Position 1	2	3	4	5	6	7
lbf	Reading[a]	Deviation from position 1 reading					
1500	1173	-4	+1	+1	+1	-1	+3
1200	939	-3	0	-1	+1	-1	+2
900	703	-1	+1	+1	+2	0	+3
600	468	0	+1	+1	+2	0	+3
300	234	-1	+1	+1	+1	0	+2
0	0	0	0	0	0	0	0

[a] Arbitrary units.

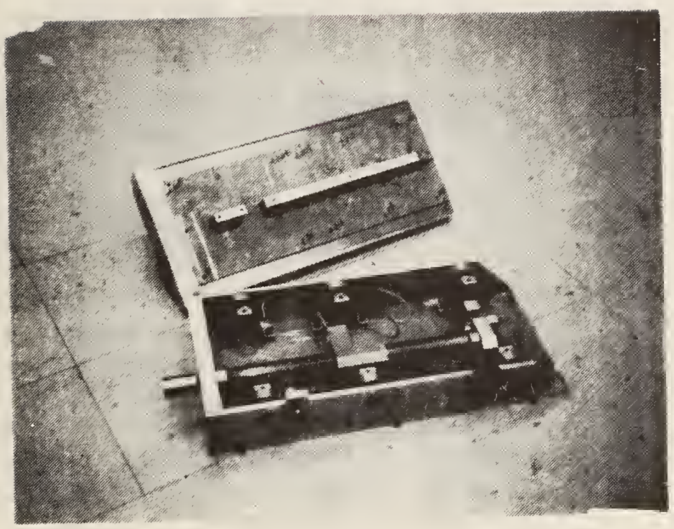


Figure 32. Modified state force plate. The platform has been removed to show the roller bearing and screw mechanism.

The lateral force acting at the test wheel should be applied to the wheel transducer during a wheel transducer calibration. If the force plate applies this lateral force during the wheel transucer calibration, the force plate should be calibrated with the lateral force applied to the plate.

4.1.3. Vertical Load Reduction

When calibrating the wheel transducer of the IRS, the reduction in vertical load is 112 pounds when the horizontal traction force is 800 pounds. There is a difference between the traction output under a varying vertical load and the traction output under a constant vertical load. Since the IRS force plate is used to calibrate wheel transducers of trailers with a variety of geometries, the plate is calibrated for a variety of H/L ratios and $F_{WL_{yo}}$ values. Values of $F_{WL_{yo}}$ from 885 to 1085 lbf are allowable within ASTM method E 274-70. A partial survey of trailer geometries revealed variations in H/L from 0.093 (Stevens Institute of Technology) to 0.147 (State of Delaware).

The force plate vertical load channel is calibrated without any horizontal traction force applied. The vertical load channel is balanced with only the weight of the plate itself acting. The calibration curve for the force plate vertical load channel, under these conditions, is shown in figure 33. The output values are in arbitrary units.

If the traction channel is balanced under no vertical load, the addition of 1085 lbf of vertical load introduces an output of nominally 11 pounds into the traction channel output. To minimize this difference the horizontal traction channel is balanced with 1085 lbf of vertical load applied. The calibration curve for H/L ratios from 0.09 to 0.15 at $F_{WL_{yo}}$ of 1085 lbf is given in figure 34.

4.1.4. Lateral Force

The IRS force plate was calibrated without lateral force being applied to the plate since use of the air-bearing platform eliminates this force component. When calibrating the wheel transducer the lateral force acting on the test wheel may be applied experimentally (see sec. 5.3).

To estimate the lateral force that would be present without an air bearing, a static trailer test was conducted where the lateral force under the free tire was measured while the state force plate which has no air bearing, was used to apply a traction force to the test tire. When the traction force was 800 lbf, the lateral force at the free wheel was 146 lbf. Since the total lateral force was 213 lbf (see sec. 2.2) the lateral force applied to the state force plate during the application of the traction force was 67 lbf. Thus the design of this force plate dictates that it be calibrated with three orthogonal components of force comprising the combined load. Consequently, a calibration fixture for this force plate must apply three forces simultaneously.

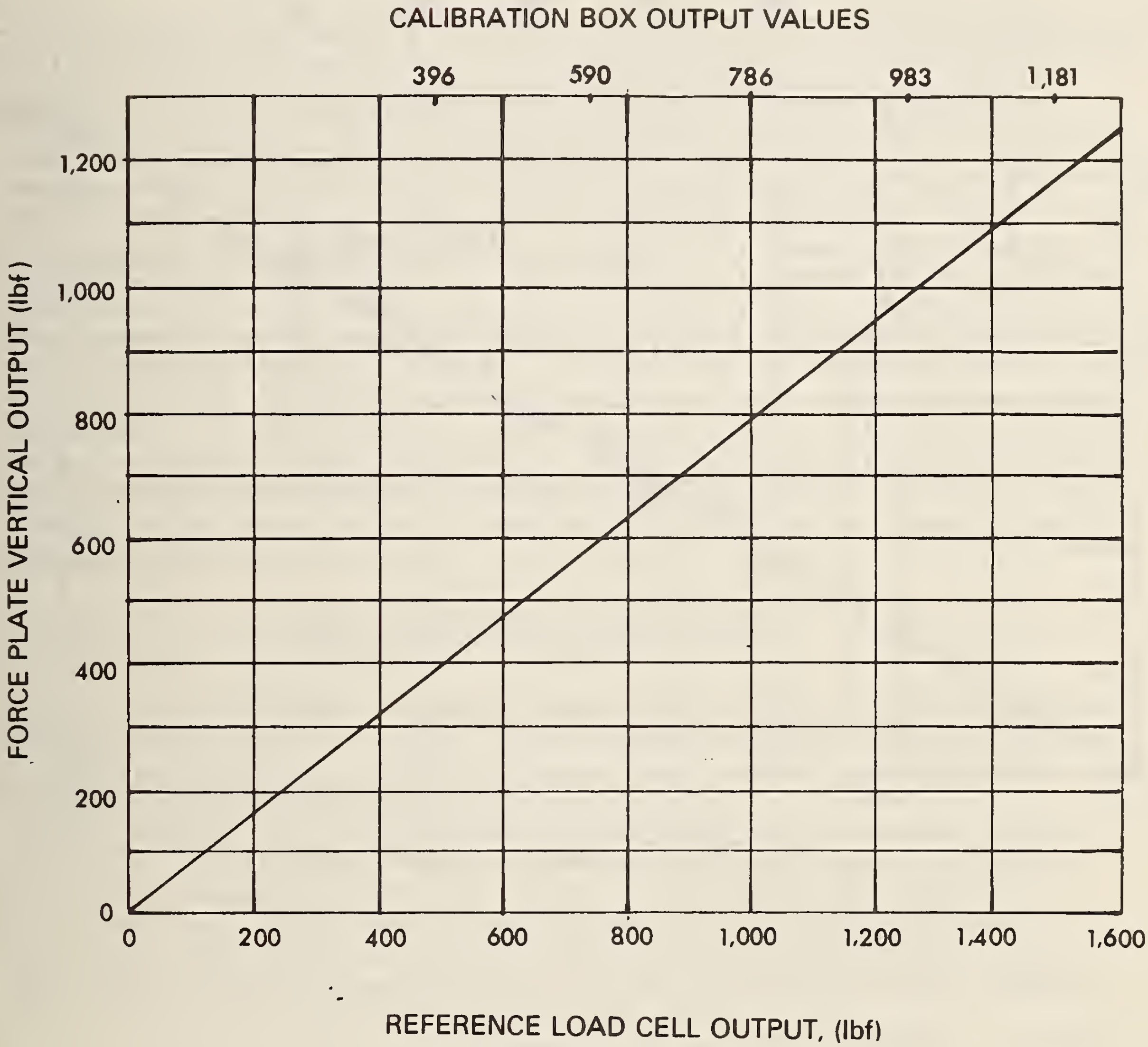


Figure 33. IRS force plate vertical load calibration.

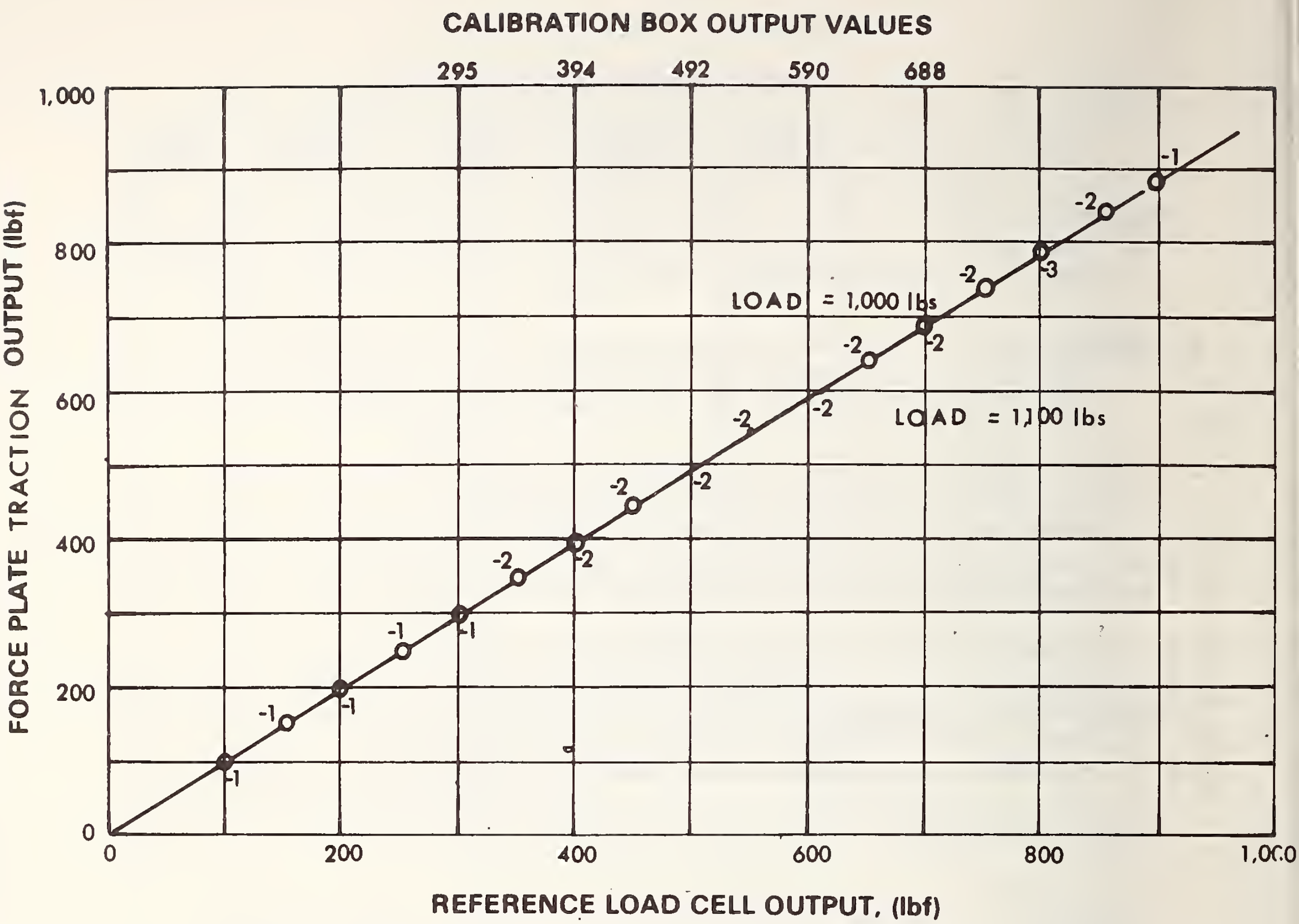


Figure 34. IRS force plate traction calibration.

Notice from equation 1 that if traction forces of equal magnitude were applied to both of the tires during use, the total lateral force generated would be zero and there would be no need to calibrate the force plate in the presence of a lateral force.

4.1.5. Force Plate Displacement

During a traction test the force plate moves if it is not restrained. It is important in the force plate calibration procedure to take the motions into consideration as well as the combined forces occuring during use (see sec. 4.2). These motions have been identified for the IRS. The rearward motion of the axle was shown in section 2.2. Note the large displacement of the force plate with respect to the ground shown in figure 35. There is also a displacement of the force plate with respect to the axle. This displacement with changes in traction force was shown in section 2.2. When the traction force is 800 lbf, the displacement is 0.3 inches. This displacement is also a function of tire temperature. The test was repeated after the tire was subjected to a five mile warm-up run. During the repeat test the tire cooled from 108 °F to 90 °F, although the test duration was only a few minutes. The displacement of the force plate with traction for the cold tire and the warmed-up tire is shown in figure 36. For consistent results the warmed-up tire temperature should be maintained during the test duration. The change in test tire radius for the two tests is given in figure 37 (also see sec. 5.6).

4.1.6. A Combined Load Fixture for Calibration of the Force Plate

The calibration of the force plate requires that a combined load be generated and measured. Since the air-bearing platform eliminates the lateral force acting on the force plate, the combined load reduces to simultaneous vertical load and horizontal traction forces. A calibration fixture for that purpose is shown, with its associated instrumentation, in figure 38. The forces are generated by means of hydraulic jacks and measured with load cells and universal digital indicators. The force plate output signals are conditioned and converted to a digital printout by means of the automatic bridge balance unit shown. Dial gages are used to maintain the attitude of the force plate surface within 0.01 inches over the length of the plate.

To obtain a datum point the universal digital indicators are preset to the desired force value by the use of the load cell calibration data. The hydraulic jacks are operated such that the desired combined forces are applied simultaneously. When this condition occurs the operator energizes the print-out command. An advantage of the fixture is that the load cells can be removed and calibrated independently.

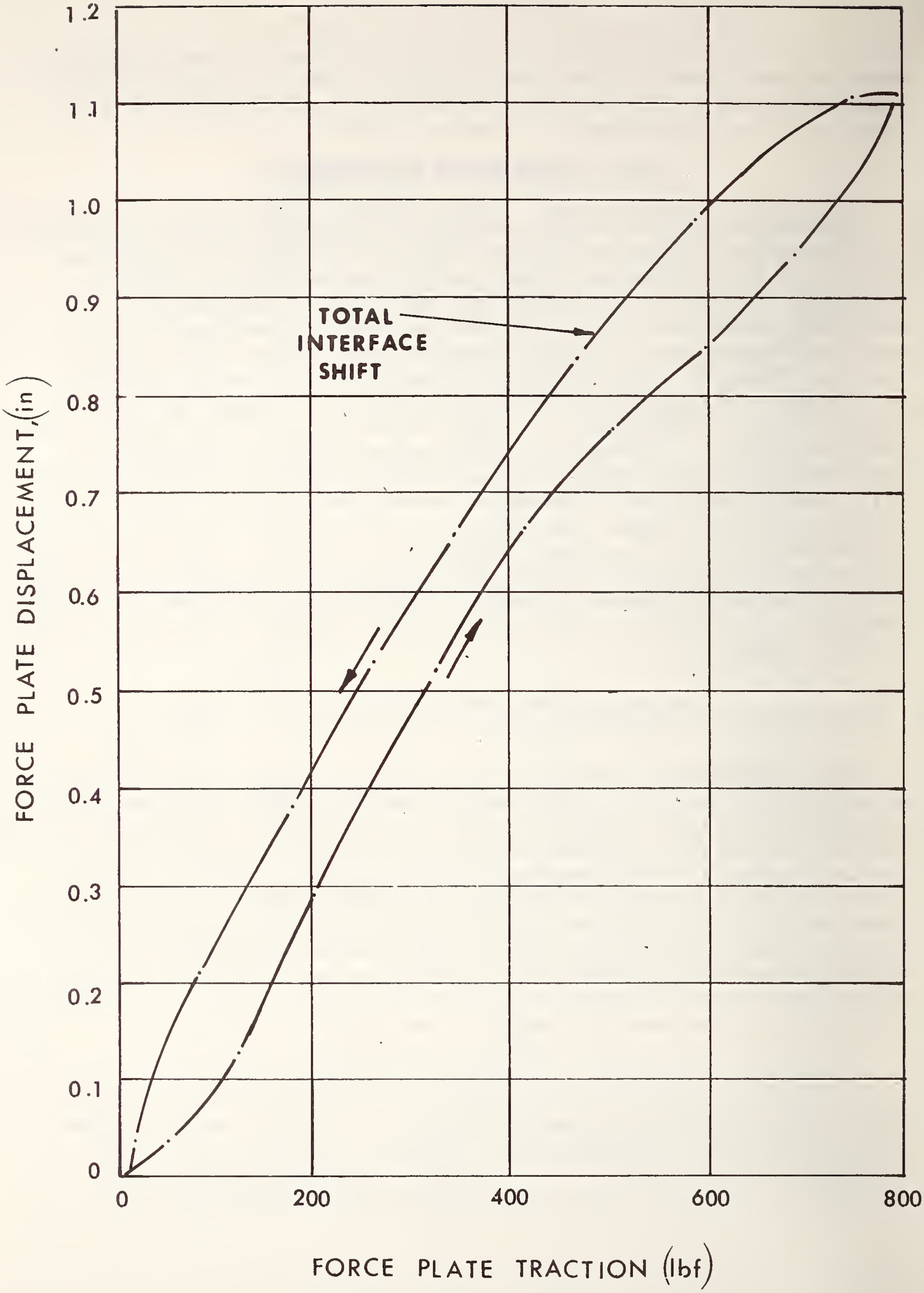


Figure 35. Displacement of the IRS force plate with respect to the ground.

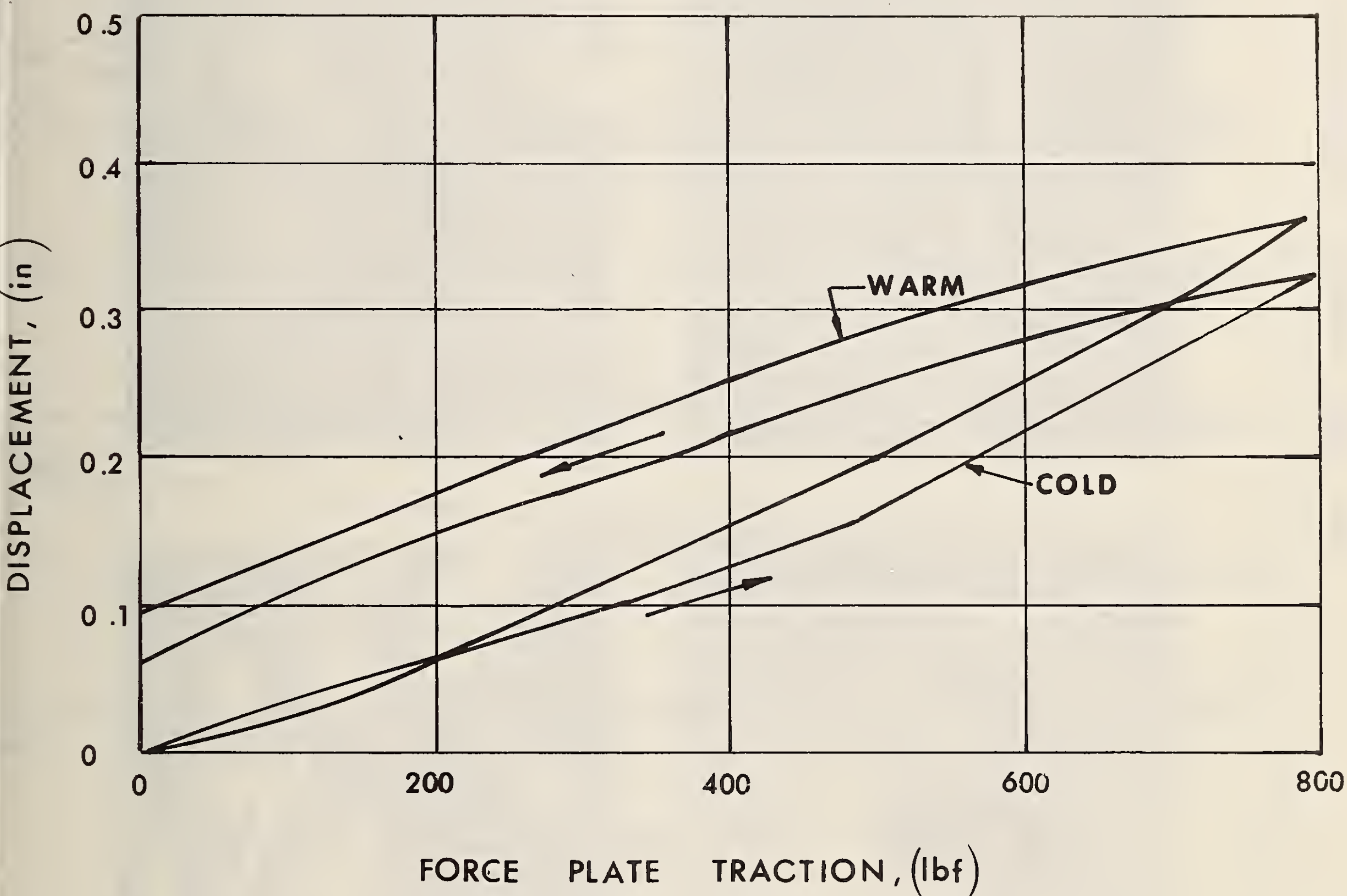


Figure 36. Displacement of the IRS force plate with respect to the axle for a warm tire and a cold tire.

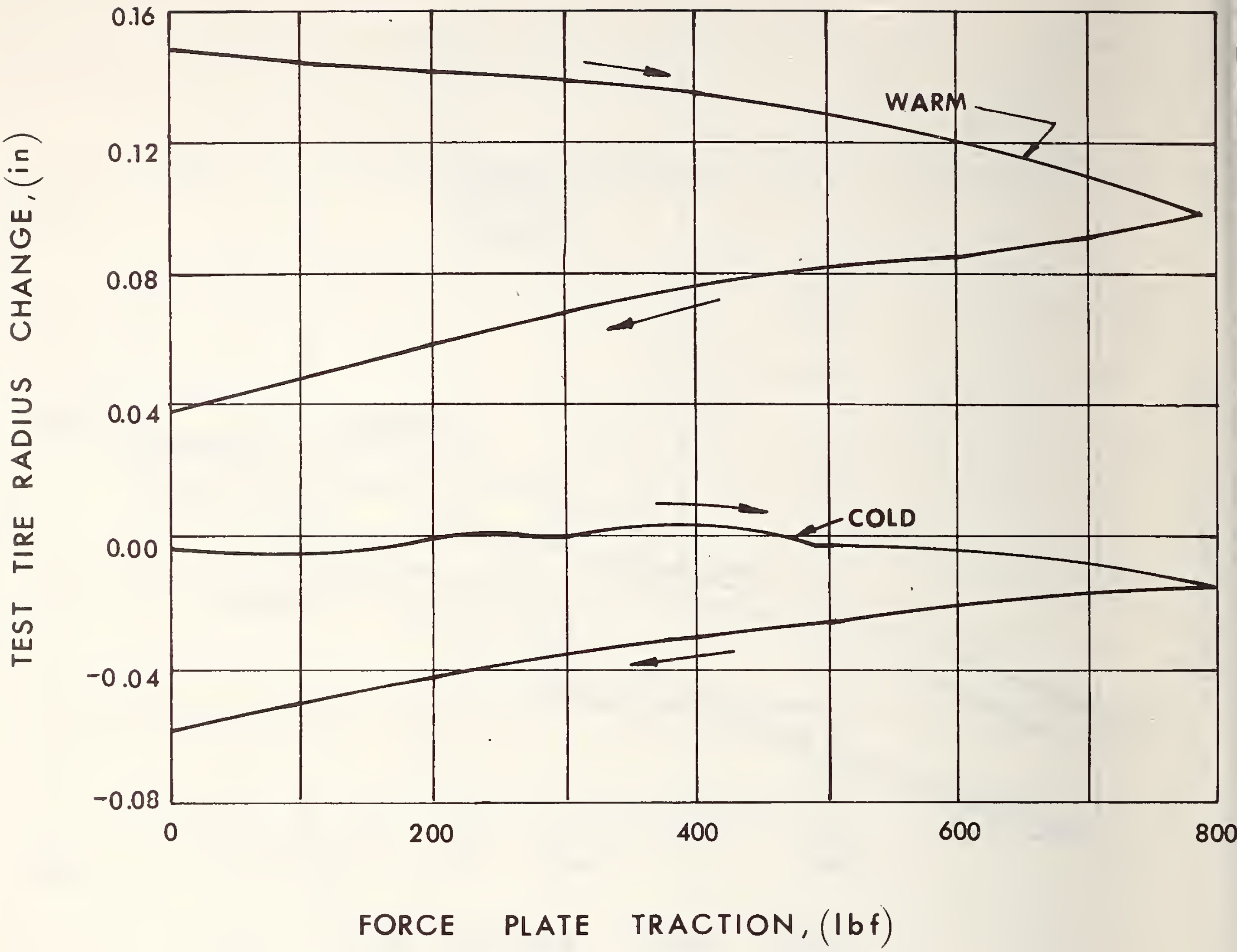


Figure 37. Change in test tire radius due to traction for a warm tire and a cold tire.

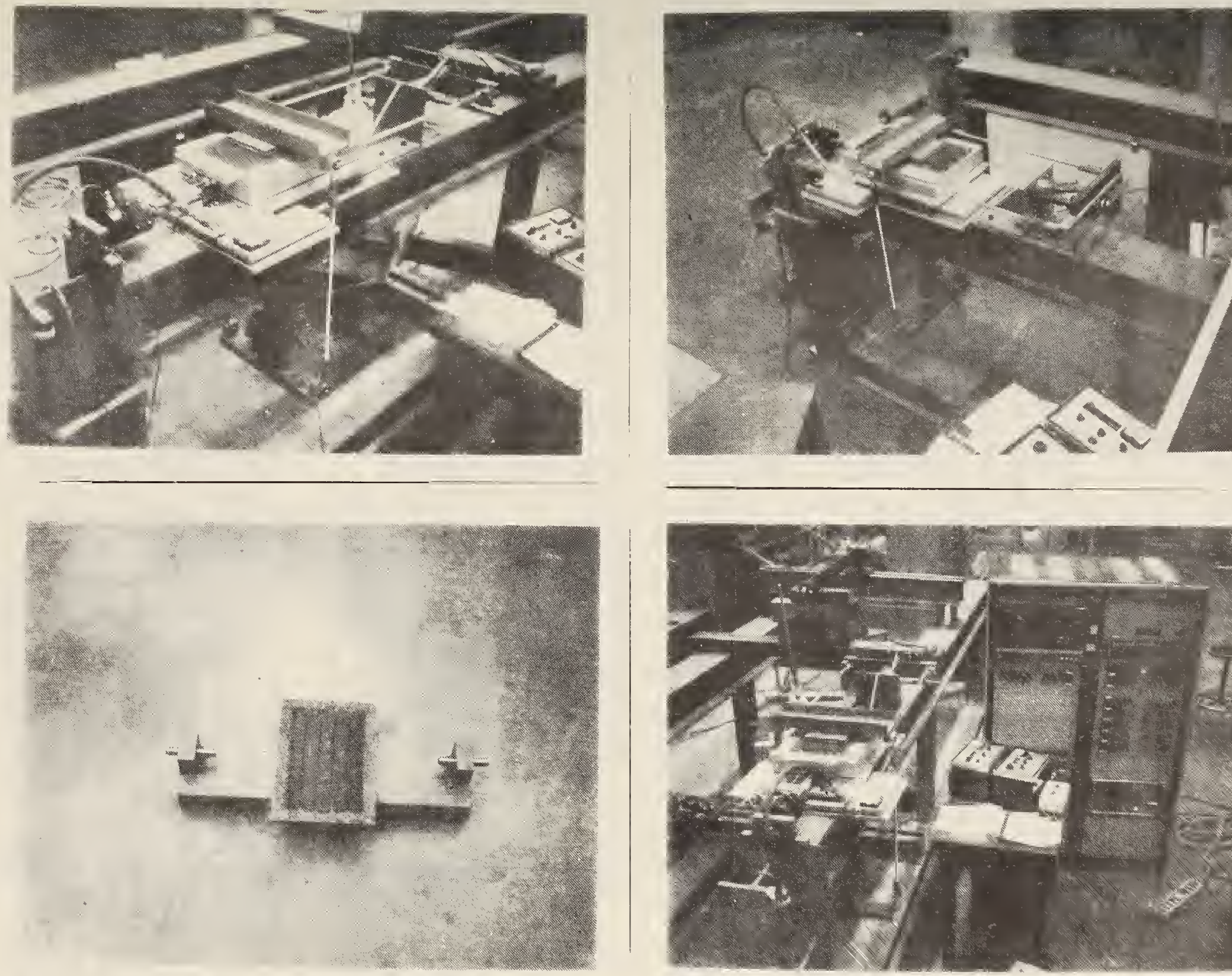


Figure 38. Calibration fixture for air-bearing force plate.

The vertical load force is applied through a tire similator which has a rubber area corresponding to that of a standard test tire sustaining a load of 1085 lbf. The horizontal traction force is applied through a spring which has nominally the same spring rate as a test tire. The rubber creeps under the combined loads and the spring allows the displacement to occur without unloading the force generated by the hydraulic jack. The force plate is calibrated while floating on the air-bearing platform.

4.1.7. Force Plate Reference Resistors

After the IRS force plate was calibrated, five shunt calibration resistors were precisely adjusted to convenient values for each channel. The purpose of each resistor is to shunt one leg of the Wheatstone bridge such that the no-load output signal with the shunt resistor connected is equivalent to the output signal obtained with a given force applied. Five resistors are used so that any nonlinearities in the instrumentation will become evident. The five points also allow the recorder instrumentation scale to be expanded and still retain three points to identify nonlinearities. The traction channel resistor values were trimmed while the force plate was subjected to a vertical load of 1085 lbf.

Resistors constructed of materials with low temperature coefficients are used so changes in the calibration values with changes in ambient temperature are reduced.

4.2. The Importance of Procedure in Calibration of the Wheel Transducer Instrumentation

4.2.1. Tow Vehicle Characteristics

The wheel transducer calibration should occur with the skid trailer mounted on the tow vehicle. It has been shown in section 2.2 that the characteristics of the tow vehicle influence the motion of the trailer during use and during a calibration test. Since the tow vehicle characteristics influence the results, the tow vehicle should be in its normal operating condition.

Tests were conducted on the IRS tow vehicle to determine the change in hitch height with changes in water load and fuel consumption. The water load results are shown in figure 39. In order to minimize the change in hitch height with water load consumption the system can be operated with the tank always nearly full. Otherwise, a linear correction for change in hitch height due to consumption of water can be made. When the water tank is full, the change in fuel has a small effect on hitch height. The effect may be larger in another system. Deadweights were placed in the cab during the tests to simulate the weight of the occupants.

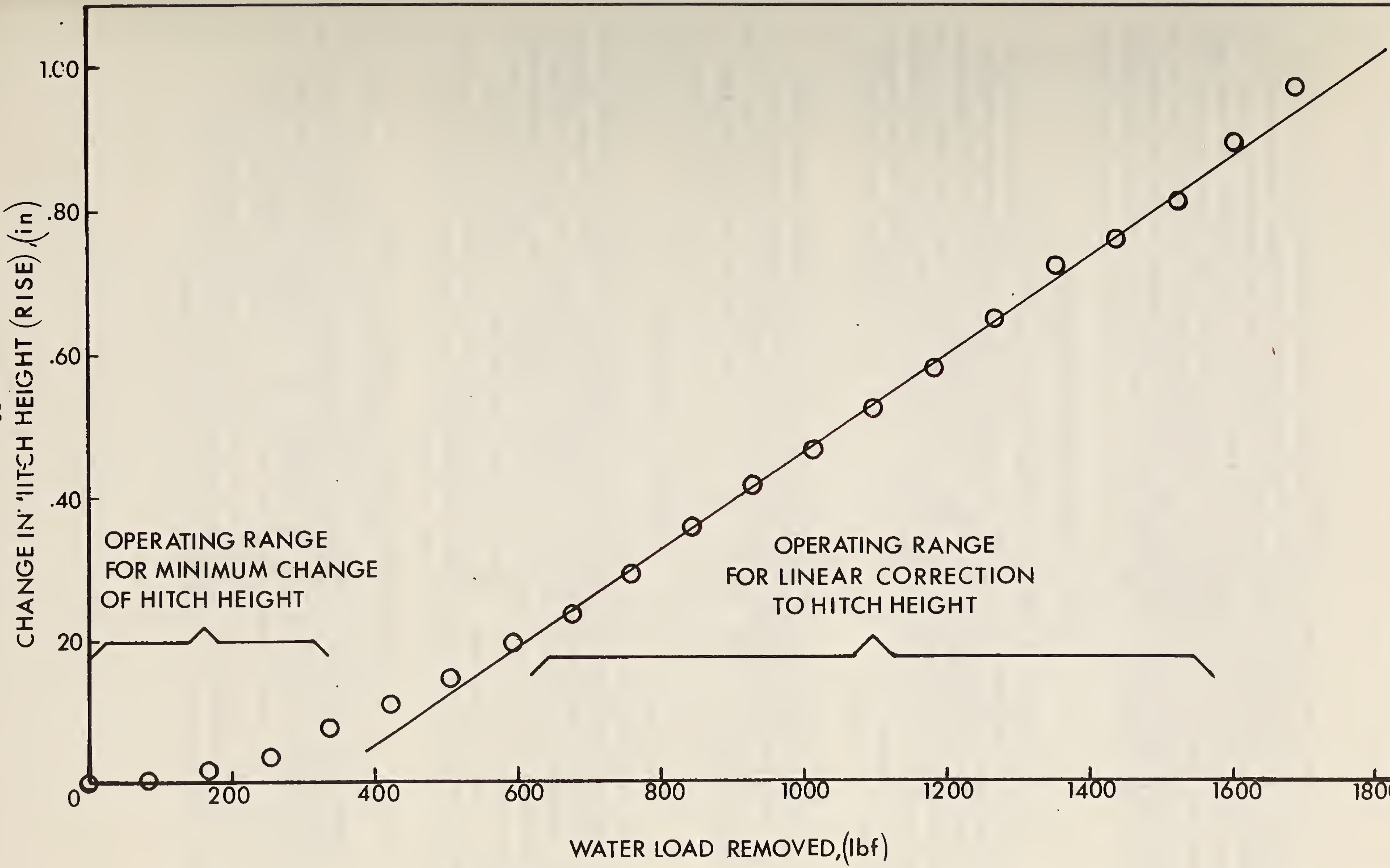


Figure 39. Change in IRS hitch height with removal of water load.

It is interesting to note that when these procedures were followed in calibrating another skid resistance measuring system, the occupant weight had a greater effect on hitch height than did the entire water load. A small truck was used as a tow vehicle, and the rear springs had been reinforced to accommodate the water load, but the front springs were not altered. Consequently, the occupant weight compressed the front springs thereby pivoting the truck and changing the hitch height. This incident supports the importance of restricting transport of cargo in the tow vehicle to further control hitch height.

4.2.2. Trailer Characteristics

The mathematical analysis of the trailer and the calibration of the force plate assumed that the at-rest forces are at their nominal values. It has been shown previously that the magnitude of crosstalk differences depends on the nominal load values. Accordingly, before the wheel transducer is calibrated, the center of gravity and weight of the trailer are trimmed so the trailer wheel load forces are both 1085 lbf and the vertical force at the hitch is within 100 to 200 lbf when the trailer is properly oriented.

This operation is best conducted with an air-bearing force plate under each trailer wheel. A stationary hitch ball mounted on a load cell completes the set-up for simultaneous measurement at the three points of support. The results are quite sensitive to the orientation of the trailer.

4.2.3. Transducer Orientation

The transducer must be properly oriented on the trailer, establishing the traction axis parallel to the pavement. To accomplish this, the transducer may be rotated with respect to the axle, or, the rotation may be made by a change of hitch height. In either case, the trailer is alternately lifted and lowered while the transducer is rotated until the change in output of the transducer traction channel caused by the vertical load is minimized. The adjusted transducer and trailer orientation must be maintained since, when the transducer is misalined, application of force will give rise to false outputs.

4.2.4. Force Plate Operation

Tests were conducted to compare the technique of re-orientating the air-bearing force plate before taking each datum point to the technique of a continuous recording without re-orienting. It was found that, if the force plate was always supported on a film of air, no difference in the output of the wheel transducer was evident. However, during a test, it is still necessary to maintain the force plate orientation within bounds consistent with the desired force plate accuracy.

4.2.5. Free Wheel Support

Tests were conducted to investigate if the method of support of the free wheel influenced the results. In one test, the free wheel was also supported on an air bearing with the lateral force being applied through a point on a load cell at the tire-pavement interface (sec. 2.2). In a second test, the air bearing was deactivated while the restraining point was retained. In a third test, the air bearing was deactivated and the restraining point was removed. No difference in the results of the three tests was evident.

5. MEASURED EFFECTS OF THE SYSTEM VARIABLES ON THE CALIBRATION RESULTS

The wheel transducer has been calibrated on the trailer in a static condition under rather idealized conditions. To identify the sources and the magnitude of output variations which accompany variations in system operation, a series of tests were conducted which will be described in this section.

5.1. Hitch Height Variation

It has been shown that changes in water load, fuel load, occupant load and hitch load change the hitch height with respect to the pavement. To identify the magnitude of the changes in transducer output due to changes in hitch height, the height was changed and the transducer outputs recorded and presented as in figures 40 and 41. A one-inch change in hitch height shifts the horizontal traction channel output by 8.3 lbf (fig. 40). This is due to the rotation of the transducer which accompanies the change in hitch height. The parallelogram linkages keep the transducer level with axle motion only if the trailer body remains level. Since there is 1085 lbf vertical load present, and the tangent of the pitch angle is 1/120, the change in horizontal traction output due to the component of vertical load is

$$1085 \left(\frac{1}{120}\right) = 9 \text{ lbf.}$$

The vertical load does decrease according to equation 7 with an increase in traction so the offset is slightly smaller at the higher traction forces. When the change in hitch height is upward, the component of the vertical load subtracts from the traction measurement. When the change in hitch height is downward, the component of the vertical load adds to the traction measurement.

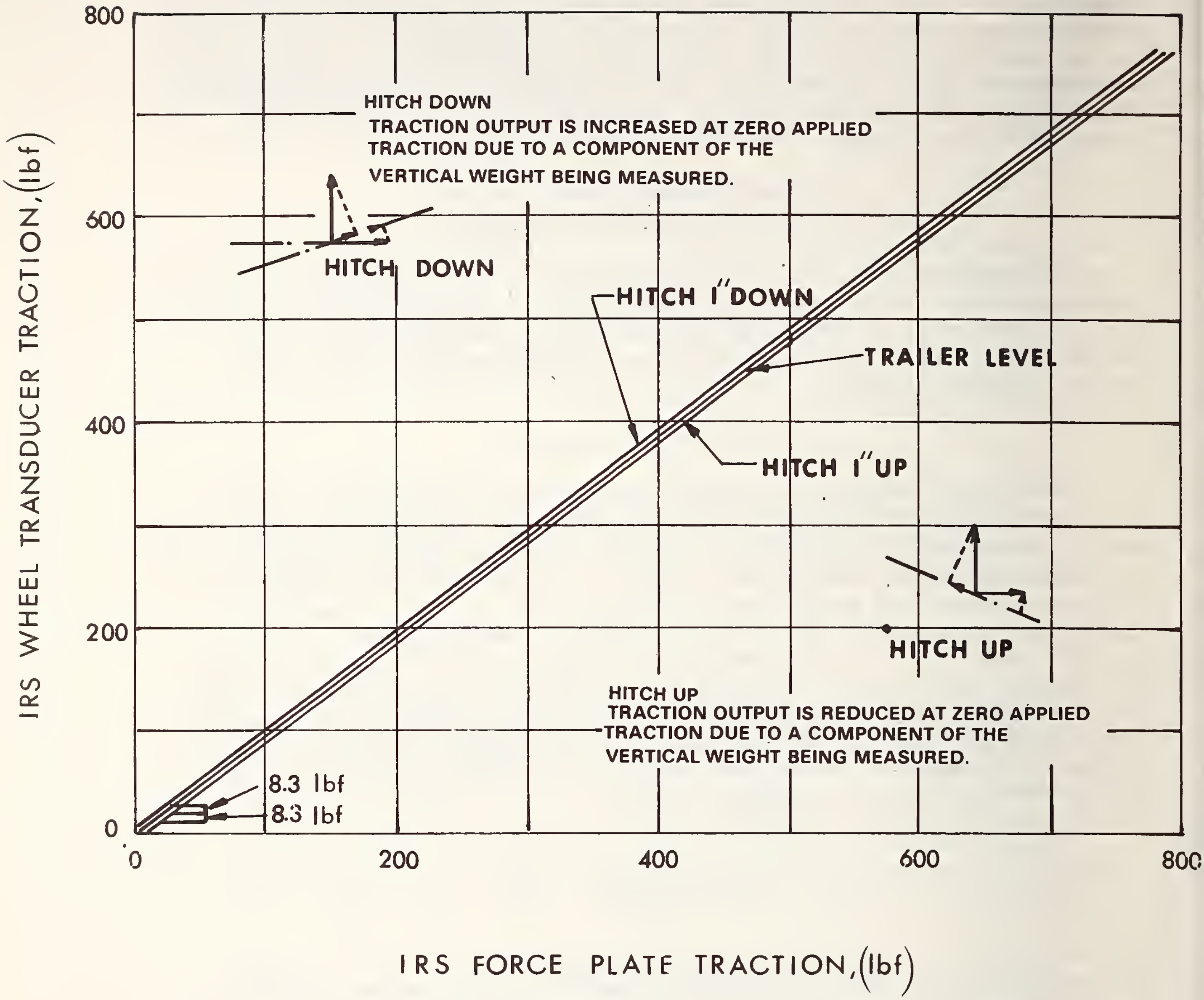


Figure 40. Change in wheel transducer traction output with hitch height.

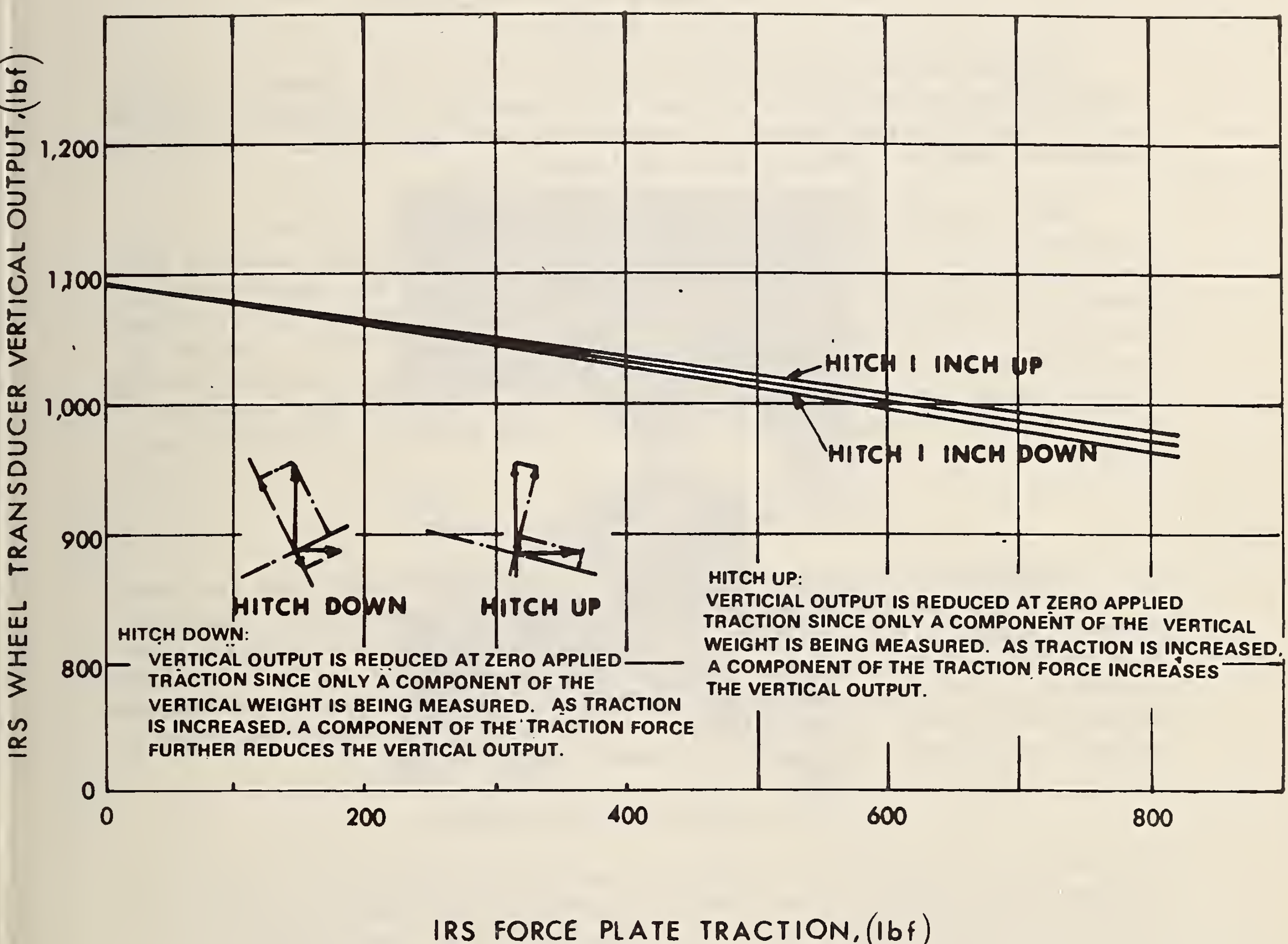


Figure 41. Change in wheel transducer vertical output with hitch height.

The change in hitch height also affects the vertical load output of the wheel transducer as shown in figure 41. At zero traction the vertical output is slightly reduced since only a component of the weight is being measured. When the change in hitch height is downward, a component of the increasing traction force further reduces the vertical output. When the change in hitch height is upward, a component of the increasing traction force increases the vertical output. As the traction increases to 800 lbf, the contribution is

$$800 \left(\frac{1}{120}\right) = 6\text{-}2/3 \text{ lbf.}$$

Changes in the vertical load on the trailer body change the pitch angle of the trailer which rotates the transducer in a manner analogous to a change in hitch height. A test to measure this effect is shown in figure 42 with the results given in figure 43.

There is also a rotation and resultant change in the wheel transducer output for a change in the shock absorber inflation pressure if the trailer is not re-oriented. As shown in figure 44, when the shock absorber air spring inflation pressure is reduced from 70 psi to 20 psi, the output of the transducer shifts 6 lbf. However, if the trailer is re-oriented at 20 psi inflation pressure, the transducer output returns to its normal characteristic. Additional test results show that the offset is proportional to the change in shock absorber inflation pressure.

5.2. Trailer Weight Variation

As mentioned in section 5.1, when a 600 pound additional load was located on the trailer body symmetrically over the axle, the traction output changed. However, when the trailer tongue was re-oriented, the transducer output returned to its normal characteristic. The effective change in hitch height was 1-5/8 inches. Since the change in transducer output with change in hitch height is nominally 8 lbf/inch, the expected change was 13 lbf. The measured change was 13 to 15 lbf.

5.3. Lateral Force Variation

Recall that the wheel transducer was calibrated in the absence of lateral force acting at the test tire-pavement interface due to the use of the air-bearing platform. This also simplified the calibration of the force plate. However, during skids, the test tire is acted upon by a portion of the lateral force generated in accordance with equation 1. To estimate the effect of the lateral force, the test shown in figure 45 was conducted with the results shown in the accompanying graph. The 200 lbf acting at the tire-pavement interface is equivalent to a tension force and a moment applied at the wheel axle. The presence of the lateral force lowered the traction output by 14.4 lbf when the traction

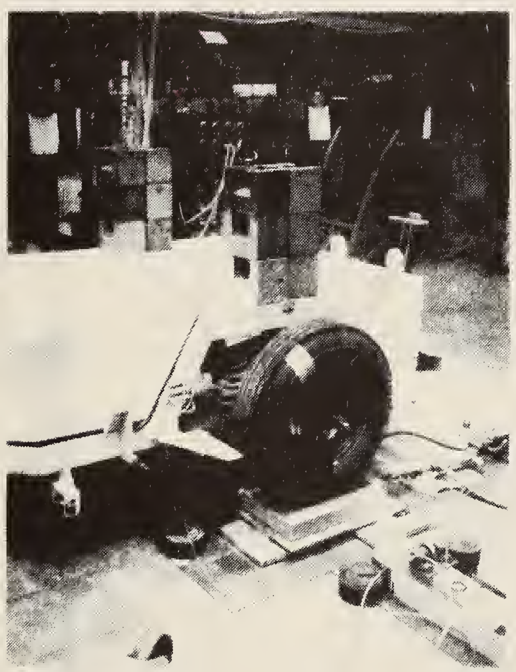


Figure 42. Increased trailer body weight test.

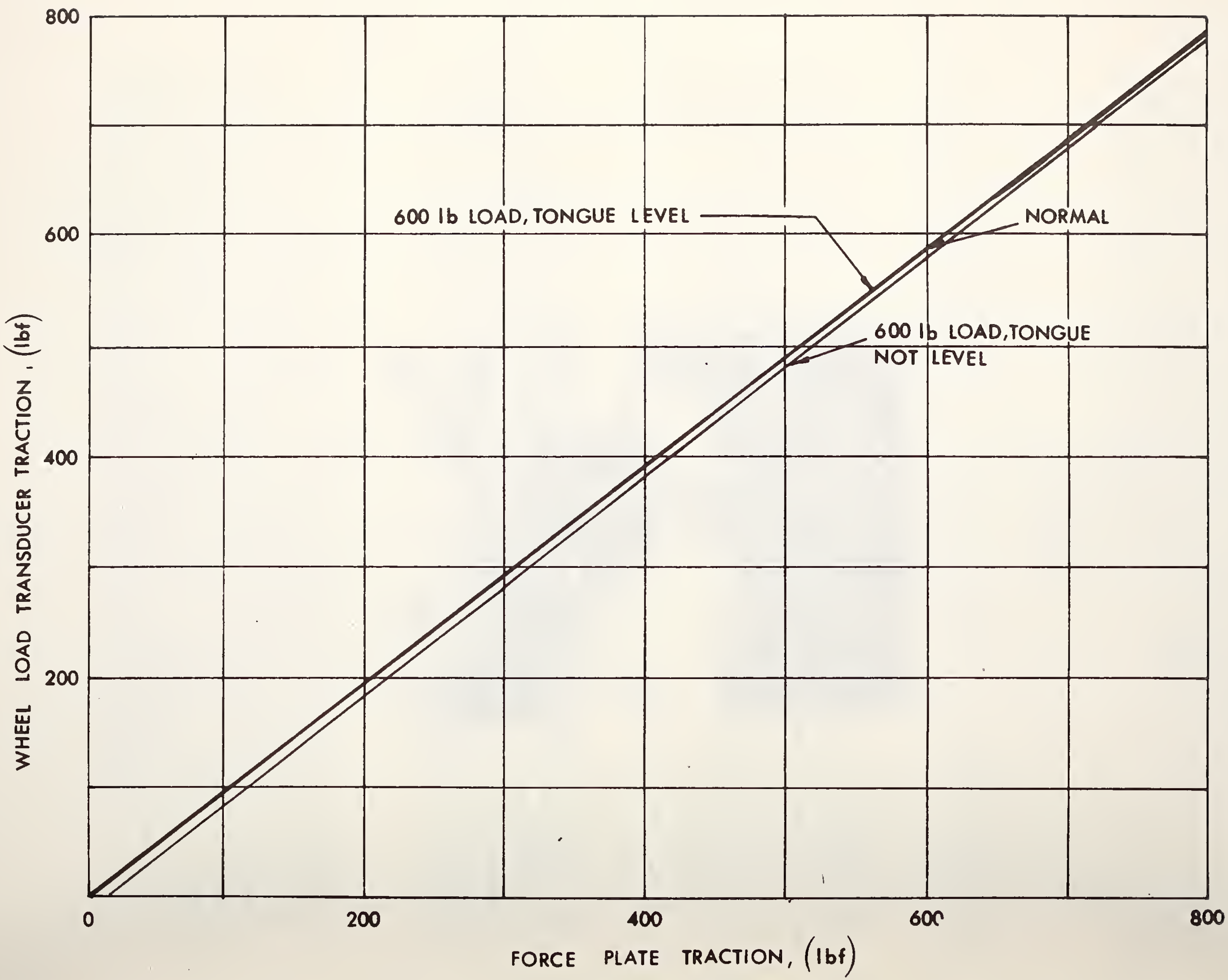


Figure 43. Change in wheel transducer traction output with change in trailer body weight.

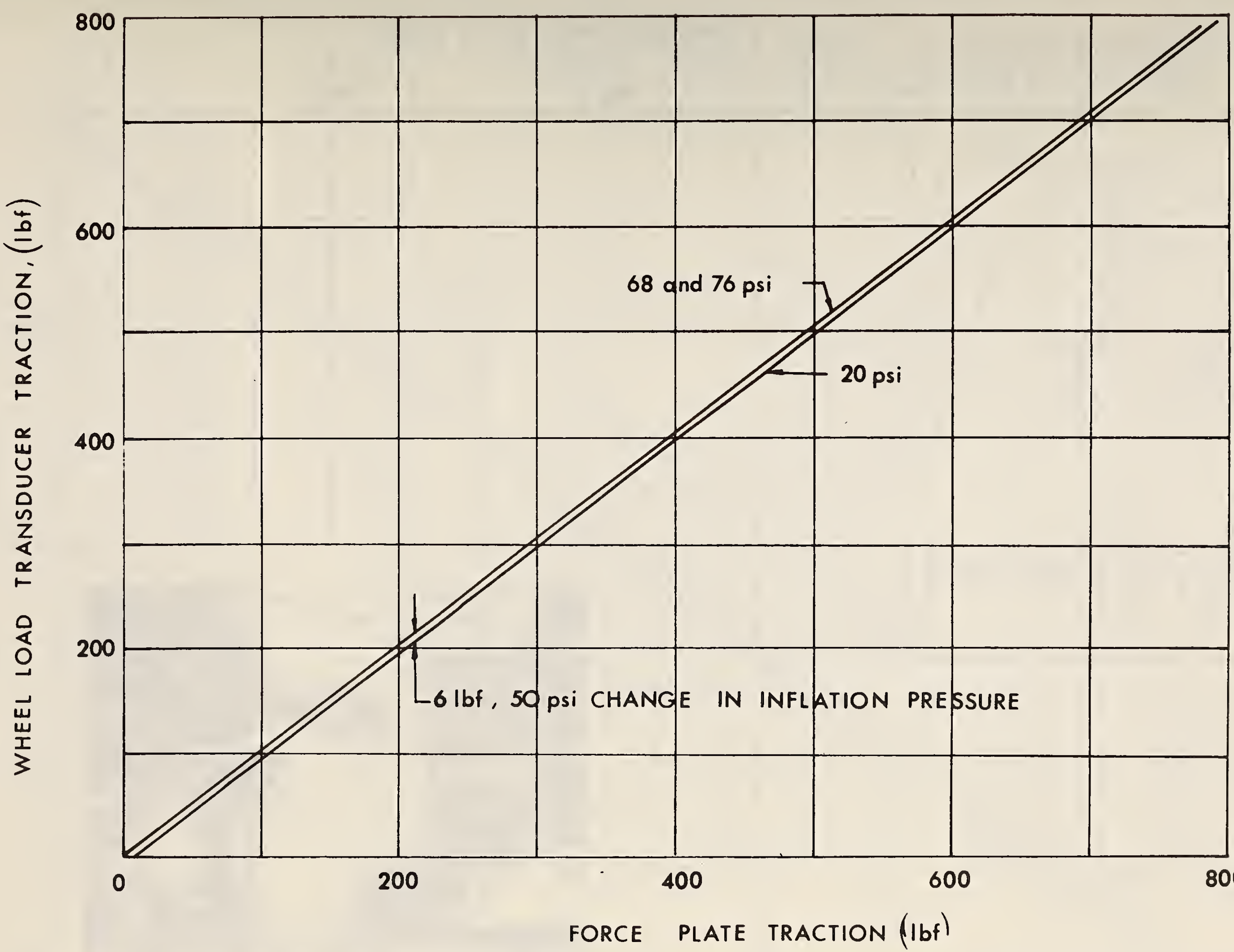


Figure 44. Change in wheel transducer traction output with change in shock absorber inflation pressure.

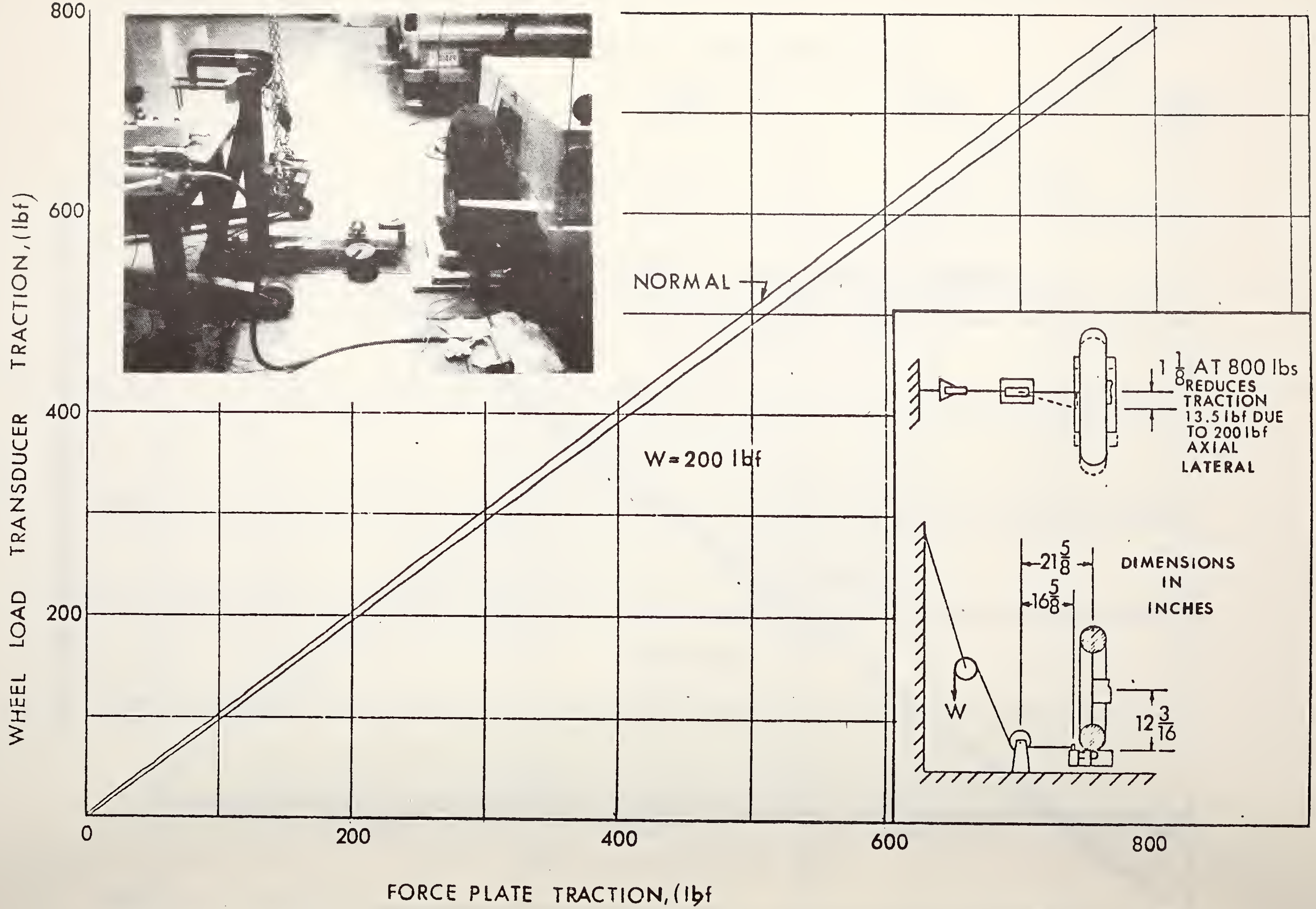


Figure 45. Change in wheel transducer traction output with lateral force applied at the tire-pavement interface.

force was 800 lbf (however, the displacement of the axle caused a component of the 200 lbf tension force in the cable to act in the traction direction. This component amounts to 13.5 lbf). To isolate the effect of the moment from the tension force at the axle, the tension test of figure 46 was conducted with the results shown in the accompanying graph. For a 200 lbf tension load, the change in output is one lbf when the traction is 800 lbf. Again, the difference between the 7 lbf change shown in figure 46 and the one lbf result is attributed to the rotation of the cable due to the displacement of the wheel. Proportional results were obtained when 100 lbf and 50 lbf were used for the tension force. Accordingly, the greater part of the change in the wheel transducer output which occurs when lateral force acts at the test tire-pavement interface is due to the tendency of that force to bend the transducer.

5.4. Test Tire Center of Support Variation

Displacement of the effective center of support in the lateral direction within the tire-pavement interface changes the output from the wheel transducer. This lateral displacement would accompany a roll motion of the trailer. To measure this effect the test tire was supported on a narrow block which was located on the force plate. Tests were conducted with the block located outboard, inboard and centrally with respect to the tire center line. The force plate was displaced laterally with the block so the force plate remained centrally loaded. The test set-up is shown in figure 47 with the results shown in figure 48. The change is greater as the moment arm about the transducer is increased tending to bend the transducer more. The lateral displacement introduced an offset and a change in slope in the traction output test results. The change between run 1 and run 2 is nominally small. The runs should not be compared by using only the change in slope values. The result of both offset and slope must be compared.

5.5. Test Tire Inflation Variation

The wheel transducer output changes with changes in test tire inflation pressure. The test wheel radius also changes with inflation pressure. The test results are shown in figure 49. The coefficient of change is nominally 1/5 lbf/psi change in inflation pressure. Since a change in wheel radius tilts the trailer, a re-orientation of the trailer may eliminate the effect.

5.6. Test Wheel Temperature Variation

Two series of tests were conducted to investigate the effect of test wheel temperature on the wheel transducer calibration. The first concerned the change in radius between a warm and cold test tire and the change in the force plate displacement when the test tire was warm and when it was cold (sec. 4.1.5). In the second series the test wheel was enclosed and the temperature within the enclosure was raised. The enclosure was free to move with the force plate as shown in figure 50.

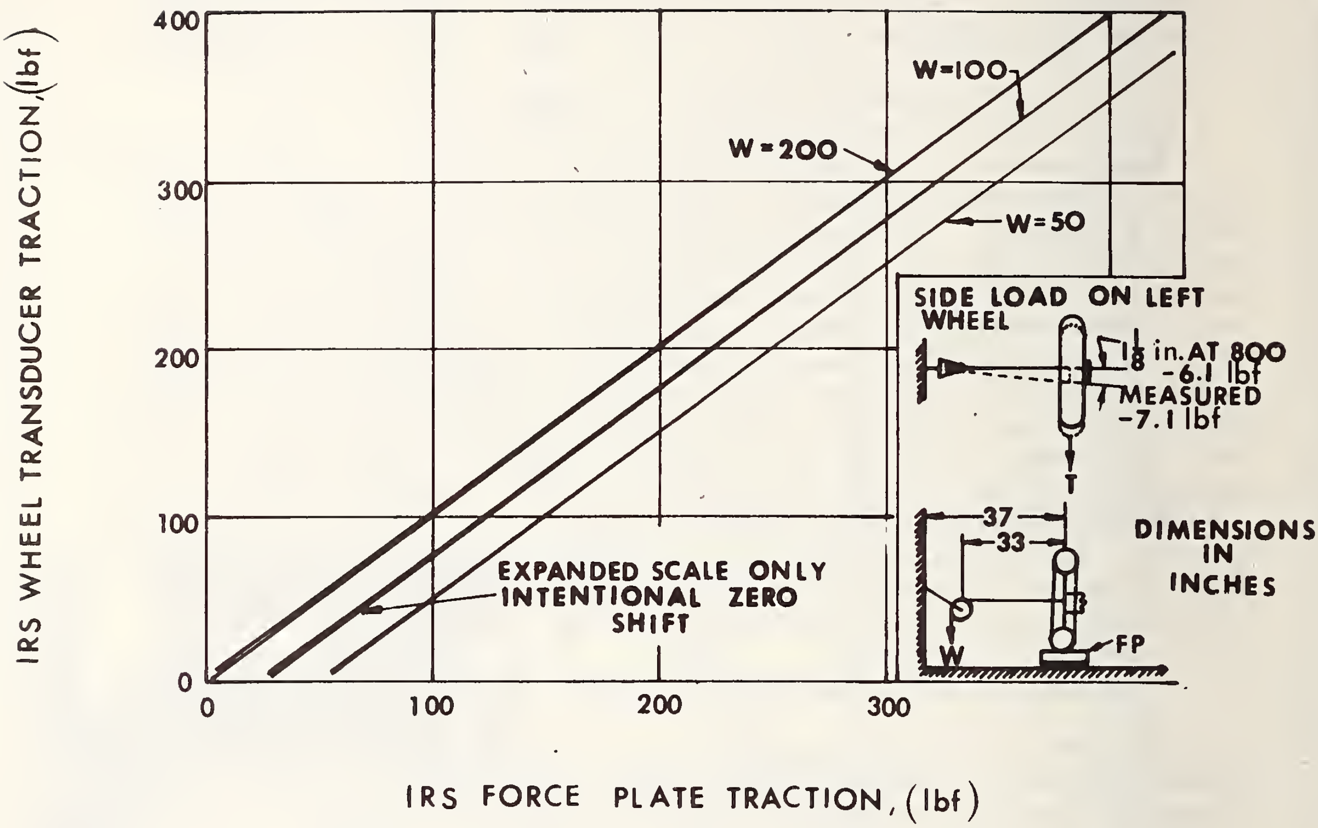
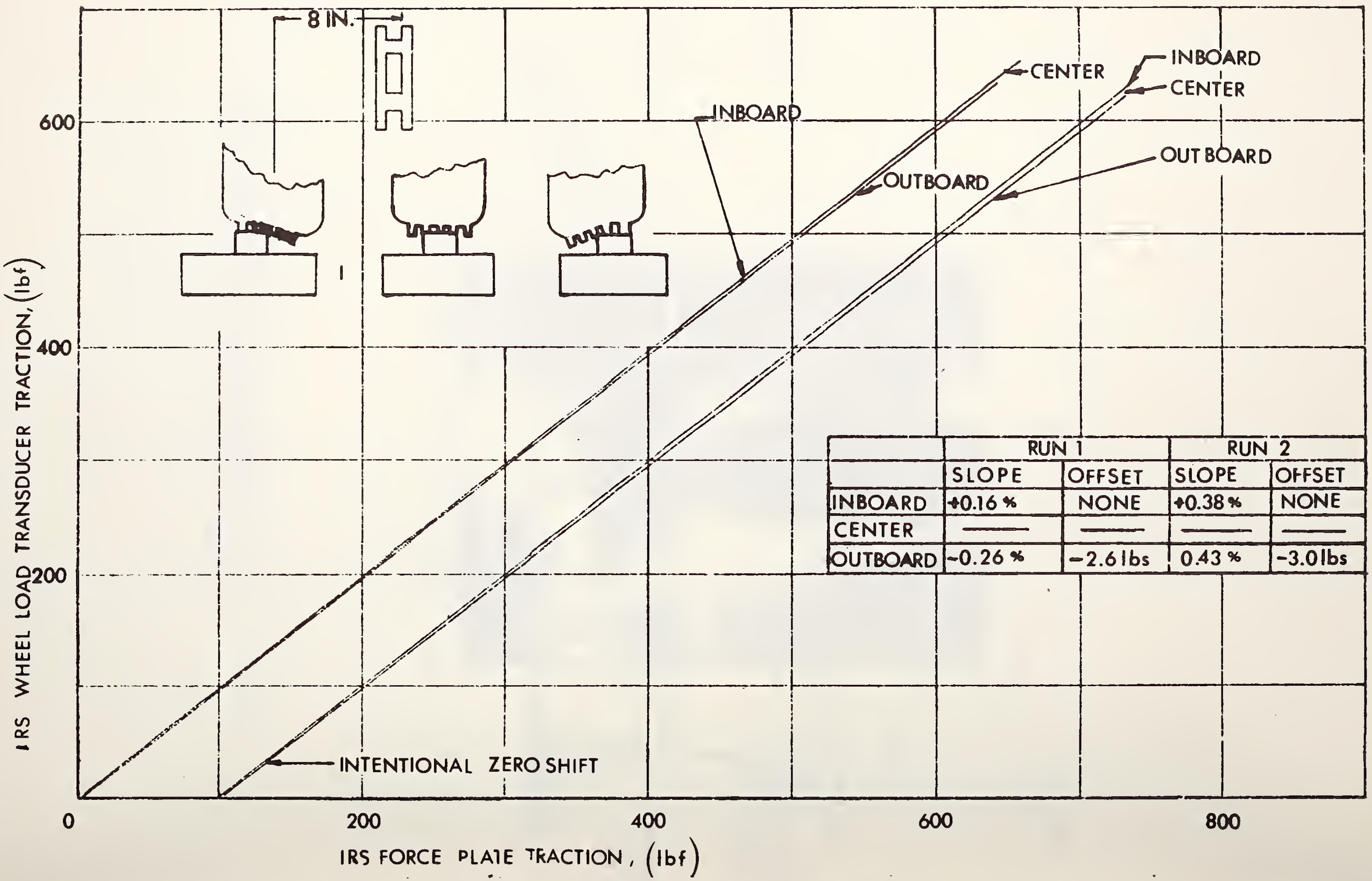


Figure 46. Change in wheel transducer traction output with lateral force applied at the test wheel hub.

Figure 47. Lateral displacement of the effective center of support of the test tire.



	RUN 1		RUN 2	
	SLOPE	OFFSET	SLOPE	OFFSET
INBOARD	+0.16 %	NONE	+0.38 %	NONE
CENTER	———	———	———	———
OUTBOARD	−0.26 %	−2.6 lbs	0.43 %	−3.0 lbs

Figure 48. Change in wheel transducer traction output with lateral displacement of the center of support of the test tire.

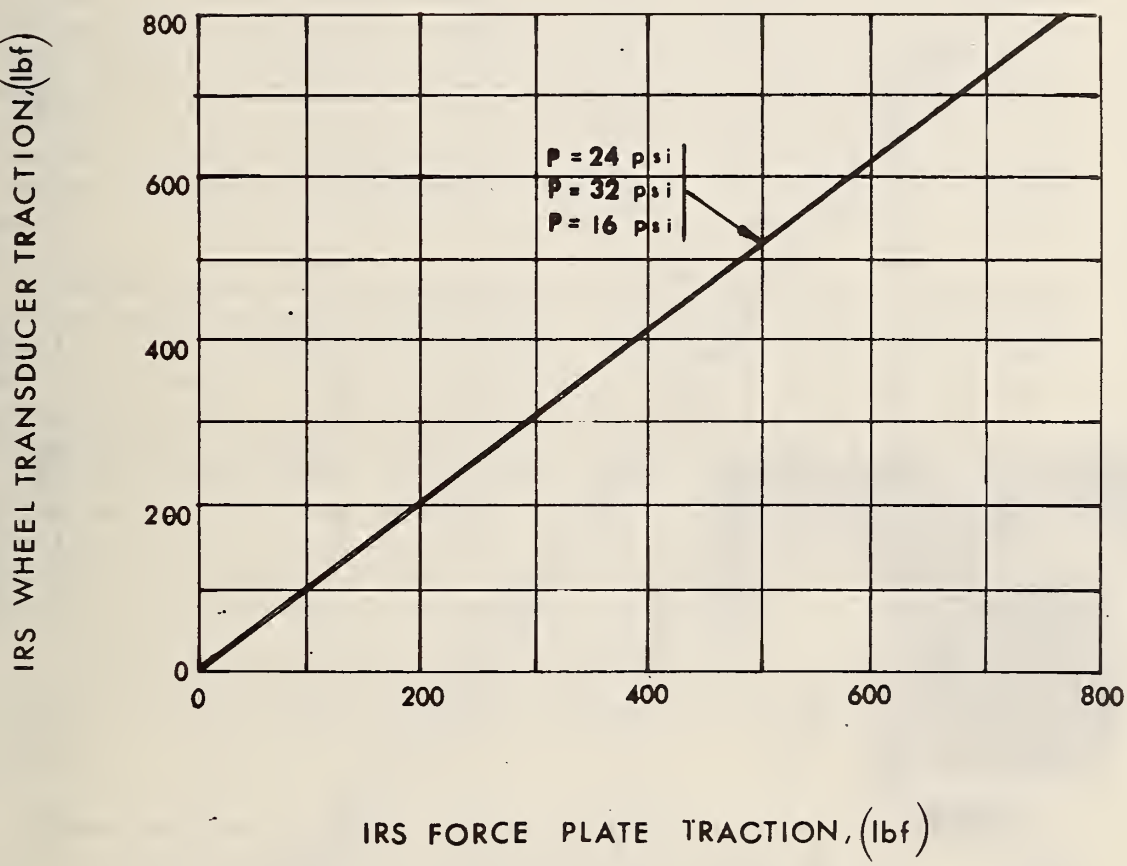


Figure 49. Change in wheel transducer traction output with test tire inflation

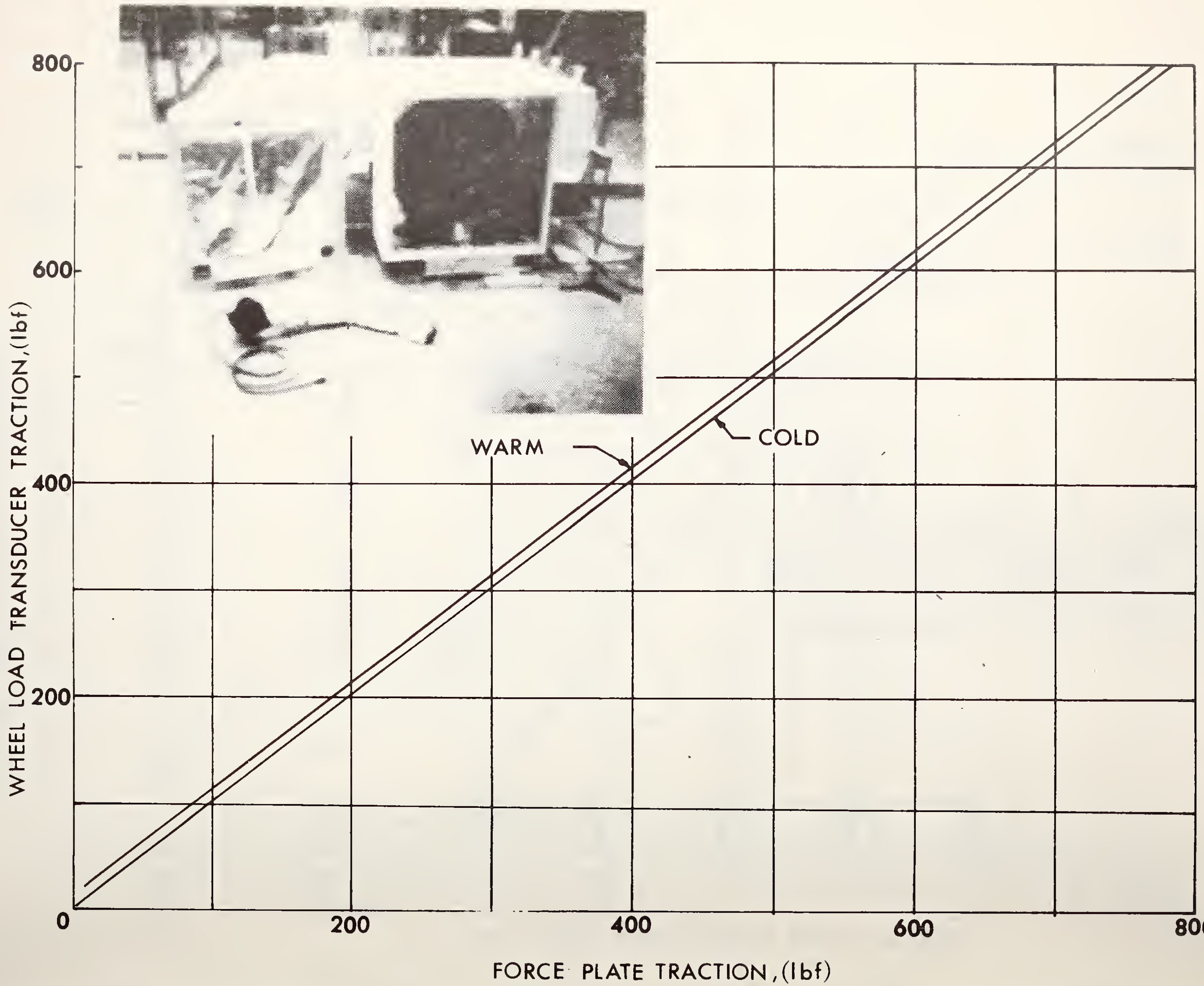


Figure 50. Change in wheel transducer traction output with test tire temperature.

As the temperature increased to approximately 230 °F, the traction channel output shifted 12 lbf, also shown in figure 50. A thermometer touching the wheel transducer surface indicated 104 °F. Since the transducer was located outside the enclosure, heat from the test wheel was transferred to the transducer establishing a temperature gradient across the transducer. Subsequent temperature tests of the wheel transducer alone, in an oven of uniform ambient temperature, indicated a temperature coefficient of 0.14 lbf offset per °F in the traction channel and 3 lbf offset per °F in the vertical load channel.

6. SUMMARY AND CONCLUSIONS

This report has described the static calibration of one skid resistance measuring system (the IRS) designed to meet the requirements of ASTM method E 274-70. The response of this system to static traction force has been quantified. Operating variables have been identified which should be controlled during calibration and use of the system. The effect of the variables on the response has been quantified. Calibration and control procedures which minimize errors and lead to increased confidence in the results have been described. The procedures can be adapted for use with any similar skid resistance measuring system.

Equations of static equilibrium for the skid trailer have been derived and experimentally verified. The motions of the trailer under static loading have been quantified. The results of the measurements may be the basis for design modifications for improved performance. The motions have been shown to be influenced by deflection of the tow vehicle in response to forces at the hitch and by deflection of the free trailer tire. To include these effects, skid trailer calibration should be conducted with the trailer hitched to the tow vehicle and the tow vehicle should be in its normal operating configuration. The characteristics of the tow vehicle tires and of the free trailer tire should be controlled in addition to the test tire characteristics.

It has been shown that a force plate used as a calibrator must itself have been calibrated under conditions covering its use with the trailer. A method for calibrating the IRS force plate has been described.

The effects of system operating variables on the IRS wheel transducer traction calibration are summarized in table 3.

Table 3. Effects of system operating variables on the IRS wheel transducer traction calibration

Operating variable	Effect on traction output
Change in hitch height	
Upward	-8.3 lbf / in
Downward	+8.3 lbf / in
Change in vertical load on trailer body	$\frac{-14 \text{ lbf}}{600 \text{ lbf vertical}}$
Presence of lateral force at test tire-pavement interface	$\frac{-14.4 \text{ lbf @800 lbf}}{200 \text{ lbf lateral}}$
Lateral displacement of the center of support of the test tire	$\frac{-6 \text{ lbf @800 lbf}}{1.5 \text{ in}}$
Change in air shock absorber inflation pressure	$\frac{-6 \text{ lbf}}{-50 \text{ psi}}$
Change in test tire inflation pressure	$\frac{1 \text{ lbf}}{5 \text{ psi}}$
Change in test tire and transducer temperature	$\frac{15 \text{ lbf}}{135\ ^{o}\text{F}}$

7. REFERENCES

[1] Goodenow, Kolhoff, and Smithson, Tire-road friction measuring system -- a second generation, SAE paper 680137.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A variety of skid resistance measuring systems have been designed to meet the requirements of ASTM Method E 274. When these systems are compared on the same pavement, the measurements often vary widely. This report describes procedures for the calibration and control of one such measuring system, the FHWA Interim Reference System. This system employs a tow vehicle and two-wheeled skid trailer. The procedures are chosen to minimize errors, leading to an increased confidence in the measurement results.

Equations of static equilibrium for the skid trailer are derived and experimentally verified. The motions of the system in response to static force are measured and shown to depend on tow vehicle as well as trailer characteristics. Variables affecting the force calibration are identified. These include hitch height, trailer weight, lateral force on the test tire, center of support of the test tire, temperature of the test tire and force transducer, and inflation pressure.

The use of a force plate as a calibrator is described. It is shown that the calibrator must itself have been calibrated under conditions covering its use with the trailer. Calibration of the force plate under combined vertical and traction force is described.

The procedures are adaptable to other similar skid resistance measuring systems.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accident reduction, skidding; highway safety; measurement, skid resistance; pavement skid resistance; skid resistance measurement; tire-pavement interface forces; wet pavement skid resistance.

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